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High-Level Ozone Disinfection of Municipal Wastewater Effluents

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16. ABSTRACT A 20 month operating experimental program was conducted at Marlborough, Massachusetts to evaluate the feasibility, engineering, and economic aspects of achieving high levels of effuent disinfection with ozone. The ozone research pilot facility was designed to operate at a constant wastewater flow rate or with diurnal flow characteristics.

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Impacts of carrier gas ozone concentration, carrier gas flow rate, gas/liquid ratio and applied ozone dose on contactor transfer efficiencies with both effluent qualities were defined. Water quality, transfer efficiency and absorbed ozone concentration are key factors affecting disinfection performance that must be evaluated for efficient design of ozone disinfection systems.

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in cooperation with
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and
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FOREWORD

The Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

The study at Marlborough, Massachusetts evaluated the feasibility and engineering and economic aspects of wastewater disinfection with ozone under stringent bacteriological standards to levels of less than 2.2 total coliform counts per 100 ml. This project has contributed valuable technology in the wastewater disinfection field.

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Director
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ABSTRACT

A 20 month operating experimental program was conducted at Marlborough, Massachusetts to evaluate the feasibility and the engineering and economic aspects of achieving high levels of effluent disinfection with ozone. The ozone research pilot facility with a maximum flow of 4.4 l/s (70 gpm) was designed to operate either under a steady wastewater flow rate or diurnal flow characteristics.

Two effluent qualities (filtered nitrified and filtered secondary) were evaluated to assess the impacts of water quality on disinfection performance with ozone. The absorbed ozone concentration required to achieve specific levels of disinfection was found to depend on water quality. Absorbed ozone concentrations of 15 to 20 and 35 to 40 mg/l were required to achieve high level disinfection to less than 2.2 total coliforms per 100 ml with the Marlborough filtered nitrified and filtered secondary effluents, respectively. Absorbed ozone concentrations of 5 to 8 and 15 to 20 mg/l were required to achieve disinfection to 70 total coliforms per 100 ml with the filtered nitrified and secondary effluents, respectively.

Impacts of carrier gas ozone concentration, carrier gas flow rate, gas/liquid ratio and applied ozone dose on contactor transfer efficiencies with both effluent qualtities were defined. Water quality, transfer efficiency and absorbed ozone concentration are key factors affecting disinfection performance that must be evaluated for efficient design of ozone disinfection systems. Generator and contactor monitoring or mapping procedures and results employing both air and oxygen carrier gases were presented as an approach for determining the economical ozone generator operating range and optimization of ozone transfer efficiency.

This report was submitted in fulfillment of Contract No. R 804946 under the sponsorship of the U.S. Environmental Protection Agency, the Commonwealth of Massachusetts (Grant R&D 77-03 Ozone) and the City of Marlborough, Massachusetts. This report covers the period of October 1978 to June 1980, and work was completed as of November 1980.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

d	-- day
g	-- gram
g/h	-- grams per hour
g/m^3	-- grams per cubic meter
gpm	-- gallons per minute
h	-- hour
hp	-- horsepower
kg	-- kilogram
kN/m^2	-- kilonewtons per square meter
kW	-- kilowatt
kW-h/kg	-- kilowatt-hours per kilogram
kW-h/lb	-- kilowatt-hours per pound
lb	-- pound
l/s	-- liters per second
m^2	-- square meter
$m^3/m^2.day$	-- cubic meters per square meter.day
m^3/s	-- cubic meters per second
mgd	-- million gallons per day
mg/l	-- milligrams per liter
ml	-- milliliter
MPN	-- Most Probable Number
W	-- watt
W-h/g	-- watt-hours per gram

SYMBOLS

A	-- absorbed ozone concentration
BOD	-- Biochemical Oxygen Demand
^oC	-- degree Celsius
COD	-- Chemical Oxygen Demand
D	-- applied ozone dose
DO	-- Dissolved Oxygen
NH_3-N	-- Ammonia-Nitrogen
NO_2-N	-- Nitrite-Nitrogen
NO_3-N	-- Nitrate-Nitrogen
OP	-- ozone production
Q_{gas}	-- carrier gas flow rate
Q_{liq}	-- liquid flow rate
TE	-- ozone transfer efficiency
TKN	-- Total Kjeldahl Nitrogen
TOC	-- Total Organic Carbon
TSS	-- Total Suspended Solids
Y_1	-- ozone carrier gas concentration
Y_2	-- ozone exhaust concentration

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SECTION 1

INTRODUCTION

BACKGROUND

U.S. EPA Wastewater Disinfection Policy

To aid in enacting the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500), the U.S. Environmental Protection Agency defined secondary treatment as reduction of certain specific pollutants and pollutant indicators. This definition appeared in August 1973 in the Secondary Treatment Information Regulation as presented in Part 133 of Title 40 of the Code of Federal Regulations (40 CFR 133). Included in that definition of secondary treatment was fecal coliform reduction. This requirement resulted in continuous disinfection of virtually all domestic wastewaters.

Chlorine was, and continues to be used almost exclusively for wastewater disinfection. Because of this universal chlorination of wastewaters to meet Federal secondary treatment standards, there arose concerns regarding the impacts of chlorinated wastewater effluent discharge on receiving water quality(1)(2). Included in those concerns were;

1. toxic effects of chlorine residuals to the aquatic environment,

2. possible formation of halogenated organics which may be carcinogenic and/or mutagenic,

3. the general need for disinfection where human contact was either remote or only seasonal.

There was also a justifiable concern regarding the general safety of large amounts of chlorine transport and storage. Concern about chlorinated effluents has led to the incorporation of dechlorination in some chlorination systems. This approach requires additional chemicals, results in additional cost to the disinfection process, and does not prevent the formation of potentially toxic chloro-hydrocarbons.

Realizing that the above-mentioned concerns were legitimate, EPA established a Task Force on Wastewater Disinfection early in

1974(3). The objective of this task force was to prepare a summary report for the Office of Water Program Operations to develop necessary background information establishing the EPA policy on secondary treatment disinfection.

Among the major conclusions of the Task Force report were:

1. Disinfection is necessary when wastewater is discharged to receiving waters with the following uses;

   a. water supply

   b. recreation

   c. irrigation

   d. shellfish harvesting.

2. The need for wastewater disinfection when discharging to a receiving water not employed for the above purpose should be evaluated on a case-by-case basis.

3. Chlorine is a reliable disinfectant to meet bacteriological standards, but it does pose toxicity problems to aquatic life and produces possible carcinogens to man.

Among the recommendations of the Task Force were:

1. Disinfection requirements of wastewaters should be established on a case-by-case basis.

2. EPA should encourage the use of and the research into alternatives to chlorine for disinfection. Ozone should be given a high priority as an alternative.

There were two significant results of this thorough Task Force report. The first was that, in July 1976, the fecal coliform limitation was deleted from the definition of secondary treatment. This ended the requirement of continuous disinfection and allowed for a case-by-case evaluation of the need for disinfection. Disinfection standards could then revert back to the State standards that existed prior to the Secondary Treatment Information Regulation, or could be reevaluated in light of the concerns over chlorination expressed above as well as the water quality of the receiving stream.

The second significant result of the EPA Task Force Report was that the EPA actively pursue a research and development effort investigating the alternatives to chlorine for wastewater disinfection. Included in this program were the following research projects on ozone (4):

Location	General objective
Estes Park, Colorado	Cost-effectiveness of air generated ozone disinfection of tertiary effluent.
Mahoning County Sanitation District, Youngstown, Ohio	Cost-effectiveness of oxygen generated ozone disinfection.
U.S. EPA Municipal Environmental Research Laboratory Cincinnati, Ohio	EPA in-house R&D evaluation of generic ozone contacting devices.
Marlborough, Massachusetts	High level ozone disinfection.

Wastewater Disinfection Standards

Public health and protection of the aquatic and human environments should be the overriding considerations affecting disinfection requirements. Disease transmission via the aquatic route including recreational water, drinking water, and seafood from polluted water has been and continues to be a problem. The disinfection process, through the destruction of pathogenic agents, provides a barrier to possible waterborne disease before the wastewater is released to the environment. Thus, from a disease prevention standpoint, the disinfection process becomes the most important unit process in the wastewater treatment system.

The effluents from many municipal wastewater treatment plants could impact on shellfish waters, with serious potential threats for public health and local shell-fishing industries. Shellfish concentrate pollutants from the aquatic environment with the result of shellfish quality being directly related to the quality of the overlying waters. Since shellfish are frequently eaten uncooked or partially cooked, maximum protection must be provided for shellfish waters receiving effluent discharged from municipal treatment facilities. In the past there have been numerous typhoid fever and infectious hepatitus outbreaks associated with the consumption of wastewater contaminated shellfish(5)(6).

As a result of the 1924-1925 typhoid epidemic resulting from shellfish contamination(5), and due to several other less severe incidents related to shellfish contamination, a National Shellfish Sanitation Program was established by the Public Health Service to protect the quality of coastal shellfish beds. The 1964 National Shellfish Sanitation Workshop defined the bacteriological water quality for approved shellfish areas (those areas where shellfish may be taken for direct marketing) as having a total coliform mean Most Probable Number (MPN) value not exceeding 70 per 100 ml. In 1977 a fecal coliform median concentration of 14 MPN per 100 ml with not more than 10 percent of the samples exceeding 43 MPN per 100 ml was recommended for approved shellfish waters by the U.S.

Environmental Protection Agency(7). These fecal coliform levels were based on an extensive total coliform to fecal coliform correlation study and correspond to a median total coliform level of 70 MPN per 100 ml.

Some states have adopted even more stringent disinfection requirements than 14 MPN per 100 ml for mean effluent fecal coliform levels. Since November 1976, the Maryland Department of Health and Mental Hygiene has required all Facilities Plans to provide for disinfection to total coliform levels of 3 MPN per 100 ml unless special dispensation from the Department is granted(8). This high level disinfection is applicable to both coastal and inland waters but is geared toward protection of the State's intensive shellfish industry. The California State Department of Health "Uniform Guidelines for Sewage Disinfection" incorporates consideration of dilution, receiving water quality, and beneficial uses in disinfection requirements, which results in varying disinfection standards for different discharge situations(9). The standard for nonrestricted recreational use of wastewater and shallow ocean discharges in close proximity to shellfish areas specifies a 7-day median total coliform of 2.2 per 100 ml or less at some point in the treatment process.

The numerical standards of 3 and 2.2 MPN per 100 ml correspond to total negative results employing the 3-tube-3-dilution test and the 5-tube-1-dilution test, respectively, for MPN determination(10). Therefore, both stringent numerical standards are essentially equivalent, depending on the tube-dilution test procedure employed. Disinfection to such low total coliform counts is defined in this study as high level disinfection.

High-Level Disinfection with Chlorine

Chlorination has generally proven to be the least expensive and most widely practiced effluent disinfection process. Where dechlorination and/or post aeration requirements exist, chlorine is not always the least expensive alternative. In a report by the California State Department of Health to the State Water Resources Control Board on March 22, 1976 concerning bacteriological standards for municipal effluent discharges,(9) it was stated that effluent discharges with a total coliform mean level of 23 MPN per 100 ml were generally obtainable through disinfection of secondary effluents without excessive chlorine use. This conclusion was drawn from a survey of the State's municipal wastewater treatment facilities. Failure to meet this mean level at individual plants was generally attributed to deficiencies in design of the chlorination facility and not inherent limitations in the chlorination process. Another study (3) concluded that chlorination can provide reliable disinfection of secondary effluents to mean total coliform levels of 70 MPN per 100 ml. Typical chlorine dosages are in the range of 5-10 mg/l.

Therefore, it appears that with a well designed and operated plant, chlorination of secondary effluents can attain mean total coliform levels in the range of 70 to 23 MPN per 100 ml.

White (11) reported that with varying degrees of effluent polishing (i.e., filtration), a well operated and designed secondary treatment plant can provide high level disinfection to total coliform counts of 2.2 MPN per 100 ml. It has been reported (9) that 13 secondary wastewater discharges in the State of California could meet a 2.2 per 100 ml total coliform standard. Thus, it appears that with varying degrees of secondary effluent "polishing" such as filtration, proper plant operation, and with consideration of proper design dosages and contact times, the high level disinfection required in Maryland and California is obtainable with chlorination. However, the concern has been expressed that the ammonia-nitrogen levels in secondary effluent could greatly increase the cost of high level disinfection by requiring breakpoint chlorination before successful disinfection is obtained(3).

Disinfection performance of less than 2.2 total coliforms per 100 ml is required at the San Bernadino, California secondary wastewater treatment plant. During February 1979 it was reported that chlorine doses of 40 mg/l were required to achieve the 10 mg/l chlorine residual needed to meet the coliform standard. With the reported ammonia-nitrogen levels of approximately 20 mg/l, the chlorine residual would be in the less effective combined residual form. This reported level of chlorination would also be exptected to interfere with meeting effluent standards of less than 60 mg/l chlorides. Full nitrification would be expected to significantly reduce the chlorine dose required to meet the coliform standard.

White has reported that nitrified effluents and high quality tertiary effluents can successfully be disinfected to total coliform levels of less than 2.2 per 100 ml with chlorine dosages as low as 6.0 to 8.0 mg/l providing free residuals of 1.5 mg/l at the end of 30-minute contact time (12). The chlorination facilities at the Marlborough Easterly plant (two-stage activated sludge nitrification plant), consisting of two 907 kilograms (2,000 pounds) per day gas chlorinators, a 2.2 kw (3 hp) flash mixer and two plug flow baffled chlorine contact tanks, achieved the disinfection levels reported in Table 1 during the spring of 1979. The total coliform levels varied between 4 to 214 per 100 ml over the operating conditions shown in Table 1.

High-Level Disinfection with Ozone

Ozone has been employed for the disinfection of drinking water supplies at Nice, France, since 1906. Today there are well over 1,000 drinking water treatment plants throughout the world (most plants in Europe) using ozonation for disinfection and other purposes (13). In Europe municipal wastewater effluent is not

TABLE 1. CHLORINATION OF NITRIFIED EFFLUENT AT MARLBOROUGH, MASSACHUSETTS

Parameter	Mean	Minimum	Maximum
A. Performance			
Total coliforms per 100 ml	19*	4	214
B. Operating Conditions			
Average flow, m^3/s	0.15	0.13	0.23
(mgd)	(3.5)	(2.9)	(5.3)
Average hydraulic contact time, minutes	36	24	44
Chlorine dose			
kg/d	53	35	91
(lb/day)	(117)	(76)	(200)
mg/l	4.0	2.9	6.1
Total chlorine residual, mg/l	1.5	0.5	3.0

*Geometric mean.

usually disinfected. Thus, application of ozonation for wastewater treatment is scarce in Europe at the present time. Ozone has been developed and employed for wastewater disinfection since the early 1970's (primarily in the United States). There are presently 11 operating wastewater treatment plants using ozone in the United States, 23 under construction and at least 5 in the design stage. The operational, full-scale municipal wastewater treatment plants using ozone, along with those presently under construction and design in the United States are presented in Table 2 (13). Absorbed ozone concentrations in the range of 4 to 8 mg/l have been found to achieve disinfection levels of 200 fecal coliforms per 100 ml. At the operating plants tertiary and/or advanced wastewater treatment is accomplished prior to ozonation, resulting in clean effluents with suspended solids concentrations usually less than 10 mg/l.

TABLE 2. UNITED STATES TREATMENT PLANTS DESIGNED TO USE OZONE

Operational plants	Plants under construction	Plants in design
Indiantown, FL	Oak Ridge, NY	Cleveland, OH (Westerly)
Woodslands, TX	Norton AFB, CA	Tacoma, WA
Upper Thompson Sanitation District, CO	Carmel, NY	Vale, CO
Chino Basin, CA	Potomac Heights, MD	Henrico County, VA
Palo Alto, CA	Murphreesboro, TN	Lynn, MA
Harriman, NY	Casper, WY	
Collegeville, MN	Pensacola, FL	
Mahoning County, OH	Hercules, CA	
Hunter Highlands, NY	Marion, NY	
Cotter Casville, AR	Brookings, SD	
Springfield, MO	Concord, NC	
	Delaware County, OH	
	Frankfort, KY	
	Granby, CO	
	Yaphank, NY	
	Hagerstown, MD	
	Holland, MI	
	Ocean City, MD	
	Olympia, WA	
	Rocky Mount, NC	
	Madisonville, KY	
	Indianapolis, IN (Richmond)	
	Indianapolis, IN (Belmont)	

Disinfection efficiency is a function of the amount of ozone transferred into the wastewater (absorbed ozone) which is also dependent on the water quality. Wastewater pretreatment such as filtration prior to disinfection may be required to reduce the chemical ozone demand of the wastewater and insure a consistent water quality. Bhargava, in discussing the evaluation of ozonation at the new Murphreesboro, Tennessee plant, concluded that if only 25 percent more ozone would be required to disinfect the oxygen activated sludge treatment plant effluent without filtration, that filtration prior to ozonation would not be cost-effective (14).

The Oak Ridge, New York plant (Table 2) was designed to obtain less than one fecal coliforms per 100 ml with an absorbed ozone concentration range of 30 to 40 mg/l (13). The plant design includes Neptune microfloc filtration following a rotating biological contactor system prior to disinfection.

Ghan, et al. (15) found that ozone doses of 10 mg/l or less were effective in consistently removing the first two logs (99 percent) of coliform microorganisms from secondary effluent. To obtain greater than 99 percent total coliform removal with reasonable ozone doses, they concluded that water quality considerations were important. Treatment of wastewater to dissolved COD's of 12 mg/l or less and nitrite-nitrogen values of less than 0.15 mg/l was required to obtain less than 2.2 total coliforms per 100 ml. They also concluded that the ozone contact reaction time required for bacterial kill in good quality effluent was 3 minutes or less. Relationships were shown to exist for disinfection performance as a function of the ozone dose and the ozone residuals.

Novak (16) found that trickling filter effluent treated for phosphorus removal at Indiantown, Florida could be disinfected to meet the State effluent standards of 200 fecal coliforms per 100 ml with ozone doses of 4.0 to 4.5 mg/l. Ozone doses of 6.0 mg/l were observed to achieve fecal coliform levels less than 2.2 per 100 ml. Total coliform counts of 70 per 100 ml were obtained with an ozone dose of 7.5 mg/l. These disinfection levels were successfully achieved with a contact time of one minute.

Other studies have found that in the tertiary mode, ozone has been added in sufficient quantity to achieve high level disinfection. Total coliform levels of less than 2.2 MPN per 100 ml have been obtained with secondary effluent, nitrified effluent and oxygen enriched activated sludge effluent, although ozone dosages in some cases as high as 50 mg/l were required (17). However, there is a paucity of data to assist the engineer to estimate accurately the required ozone dosages to effect high levels of disinfection of secondary effluents.

In summary, a review of current disinfection practices demonstrates a trend towards high level disinfection for the protection of high quality inland waters and coastal shellfish waters. The feasibility of chlorine to disinfect to such levels has been demonstrated. However, questions remain regarding design criteria, including: need for filtration prior to chlorination, dosages and required contact times, and the environmental effects of residual toxics and the effect of dechlorination on those toxics. The reliability of ozone to provide high level disinfection has not been well demonstrated. Contactor configuration, ozone dosages and dosage control instrumentation, residual oxidation products, and general reliability are poorly defined(3).

This report presents the data and results of the high level disinfection study performed at the Marlborough Easterly Wastewater Treatment Plant from November 1978 through June 1980.

OBJECTIVES

General

The prime objective of this research program was to evaluate the feasibility of ozone as an effluent disinfectant under stringent bacteriological standards. High level disinfection was defined as achievement of less than 2.2 total coliforms per 100 ml. Achievement of the coliform standard equivalent to the water quality standard for approved shellfish areas of 14 fecal coliforms per 100 ml was also evaluated. Feasibility was evaluated with respect to consistent attainment of the disinfection objectives.

Due to the general lack of engineering experience with ozone disinfection systems, other objectives were established to gain that experience. Such objectives included:

1. evaluation of potential process control parameters
2. evaluation of the reliability of existing ozonation equipment and monitoring instrumentation
3. identification of operations and maintenance requirements
4. evaluation of key parameters influencing ozonation system economics.

To satisfy the objectives of the study, the pilot facility operation was performed in four phases:

Preliminary Evaluation Phase
Correlation Phase

Reliability Phase
Oxygen Evaluation Phase.

Initially, the first three phases were to be performed using dried air as the carrier gas to the ozone generator. The fourth phase, Oxygen Evaluation Phase, was added to provide the capability to achieve high level disinfection of filtered secondary effluent consistently and to evaluate the economics of an oxygen carrier gas system. Detailed objectives of the four Process Demonstration Phases are presented in the following discussions.

Preliminary Evaluation Phase

This phase was conducted to investigate the feasibility of ozone as a high level effluent disinfectant. Disinfection experiments were performed on secondary, filtered secondary, and nitrified effluents.

The specific objectives designed to assess the feasibility of ozone for high level disinfection on the various effluents were to determine ozone requirements, evaluate potential process control parameters, monitor ozonation system power requirements, and evaluate basic water quality parameters (pH, chemical oxygen demand (COD), total suspended solids (TSS), turbidity, and color). Effect of ozonation on dissolved oxygen (DO) level was also monitored.

Correlation Phase

The specific objectives of this phase were to add to the data base of the first phase and to increase the number and frequency of monitoring water quality parameters. The increased monitoring was intended to determine the effect of water quality on ozone requirements for disinfection. Four separate effluents were evaluated; secondary, filtered secondary, nitrified and filtered nitrified.

The frequency of analysis of the primary water quality parameters (pH, COD, TSS, turbidity, and color) was increased. Monitoring of effluent DO levels continued through this phase of the program. In addition, ferrous (Fe^{+2}) and ferric (Fe^{+3}) iron, total organic carbon (TOC), biochemical oxygen demand (BOD), total Kjeldahl nitrogen (TKN), ammonia-nitrogen (NH_3-N), nitrite-nitrogen (NO_2-N) and nitrate-nitrogen (NO_3-N) were monitored. The latter water quality monitoring effort was performed to study ozone demand. Total organic carbon was monitored for additional

information to assist in evaluation of the effects of ozonation on organics.

Achievement of the bacteriological standard of 14 fecal coliforms per 100 ml was evaluated by monitoring performance to achieve the equivalent standard of 70 total coliform counts per 100 ml. Since the standard is written in terms of fecal coliforms, additional fecal coliform monitoring was performed during the correlation phase to confirm the disinfection performance based on the total coliform monitoring. A direct correlation of the two values based on extensive shellfish area water quality monitoring had been previously established.

Total ozonation system power requirements were monitored during this phase. Independent analysis of the air preparation equipment, ozone contactors and ozone generator was conducted. The generator was monitored over the total range of operation (gas flow range and applied voltage).

Reliability Phase

The objective of the Reliability Phase was to confirm the ozone requirements determined in the previous phases while monitoring the reliability of achieving high level disinfection. Performance reliability was evaluated with respect to consistency of attainment of high level disinfection. The reliability of the ozonation equipment and the performance monitoring instrumentation was also evaluated.

During this phase, a 24-hour per day, 5-day consecutive operations period was conducted on each of the two filtered effluent types. Filtered effluent was evaluated in this phase of the program because of the consistent suspended solids level the filtration step provided. During the continuous testing periods, night time and weekend performance evaluations were included to add to the experience of the ozonation process and ozonation equipment at low flow and low strength wastewater operation. The parameters evaluated during these continuous testing periods included; total and fecal coliforms, pH, COD, TSS, and turbidity. Power requirements for the total ozonation system were also monitored.

Oxygen Evaluation Phase

The carrier gas to the generator was changed from dried air to oxygen during this phase of the project to evaluate disinfection performance and economics with oxygen. Both filtered secondary and filtered nitrified effluents were evaluated. Particular attention was given to attainment of high level disinfection of filtered secondary effluent. During this phase,

water quality analysis included; total coliforms, pH, COD, TSS, turbidity, and DO. Power requirements for the oxygen ozonation system were also monitored.

Ozone Generator and Contactor Mapping

The performance of the ozonation equipment to generate ozone and to transfer the ozone into the effluents was evaluated to develop a basis for economic evaluation. Ozone generation was evaluated by monitoring the ozone production in grams of ozone per hour (g/h) and ozone concentration in grams per cubic meter (g/m^3) versus the power draw in watts. Monitoring was performed over the available range of gas flow and applied voltage. The power required to generate ozone only, exclusive of air handling and contacting, was monitored to define specifically the generator requirements. The total power requirements for the ozonation system were also monitored throughout the four Process Demonstration Phases.

The pilot facility contacting efficiency was also defined by monitoring the ozone transfer efficiency over the available gas flow rates and design effluent flow rates. Monitoring was performed on both filtered secondary and filtered nitrified effluents.

SECTION 2

CONCLUSIONS

Based on the results obtained during the 20 month operating period of the ozone research pilot facility at Marlborough, Massachusetts, the following conclusions are made:

1. Effluent quality evaluated throughout all disinfection experiments was characterized as filtered nitrified or filtered secondary. These two effluents were determined to be significantly different with respect to COD, NH_3-N and initial total coliform counts.

2. Good correlation was observed between total coliform reduction and absorbed ozone and between total coliform reduction and effluent total residual oxidants, irrespective of type of carrier gas.

3. The relationships between absorbed ozone and total residual oxidant concentration as compared with total coliform reduction indicate their usefulness and applicability as process control parameters.

4. Plotting log total coliform reduction (Log_{10} No/N) as a function of log absorbed ozone allows consideration of both the initial total coliform value as well as the desired or observed disinfection level.

5. Filtered nitrified effluent required absorbed ozone concentrations of 15 to 20 mg/l to achieve high level disinfection of less than 2.2 total coliforms per 100 ml. Filtered secondary effluent required absorbed ozone concentrations of 35 to 40 mg/l to achieve high level disinfection.

6. Filtered nitrified effluent required absorbed ozone concentrations of 5 to 8 mg/l to achieve 70 total coliforms per 100 ml. Filtered secondary effluent required 15 to 20 mg/l absorbed ozone concentrations to achieve 70 total coliforms per 100 ml.

7. Water quality, ozone transfer efficiency and absorbed ozone are key factors affecting ozone disinfection

performance that must be evaluated for efficient and economical design of ozone disinfection systems.

8. Transfer efficiency in the ozone contactor and power requirements for ozone generation are both related to carrier gas ozone concentration and carrier gas flow rate. Ozone transfer efficiency increased with higher ozone concentrations. However, power requirements for ozone production were greater at higher ozone concentrations.

9. Evaluations of ozone production and transfer efficiency over the expected operating conditions are important for proper equipment selection. Generator and contactor monitoring or mapping procedures and results were presented as an approach for determination of the economical ozone generator operating range and optimization of ozone transfer efficiency into the effluents.

10. The percent ozone transferred into the effluent was found to be equivalent during operation with both air and oxygen carrier gas under identical operating conditions of applied ozone dose, carrier gas ozone concentration, gas to liquid ratio and effluent flow rate.

11. At high level disinfection of secondary effluent with oxygen operation, a significant yield loss of oxygen from the ozonation system occurred (30 to 40 mg/l residual dissolved oxygen).

12. The reliability of the ozone disinfection system, with respect to; disinfection performance, process control parameters, instrumentation, and equipment was demonstrated during the pilot facility operation.

SECTION 3

RECOMMENDATIONS

1. Quality of the secondary effluent at Marlborough was very good throughout the study period. A wider range of secondary effluent quality should be evaluated for ozone requirements to achieve 70 and less than 2.2 total coliforms per 100 ml.

2. High level disinfection of secondary effluent was achieved with air operation on a limited basis due to the limiting size of the ozone generator. Investigations should be conducted with ozone produced from air to prove the effectiveness and reliability of achieving the high ozone concentrations required to yield the high total residual oxidant concentrations necessary for high level disinfection.

3. At the high applied ozone doses required for these levels of coliform disinfection, ozone transfer efficiency was lower than observed for less stringent bacteriological standards (lower applied doses). Other generic ozone contacting systems should be evaluated for comparison of transfer efficiency over the conditions required for these stringent levels of disinfection.

4. Preliminary evaluations at Marlborough indicate that disinfection beyond that which is immediately realized in the contacting system can occur due to the disinfection potential of the total residual oxidants produced. Further investigations are required to evaluate the alternative possibility of providing additional holding time to reduce the ozone dose requirements for achieving high levels of disinfection.

5. Low power requirements were observed for ozone production with the equipment employed in this study. One possible explanation could be the low pressures observed in the generator (slight negative pressure ranging from 0.1 to 1.5 mm Hg with air operation and slight positive pressure of less than 6.9 kN/m^2 (1 psi) with oxygen operation). Effects of pressure on ozone production should be evaluated.

6. Water quality effects should be quantified when evaluating specific ozone applications since poor water quality can increase ozone transfer efficiency and yet yield poor disinfection.

7. During cost evaluation of ozone disinfection systems, analysis should be conducted for nitrification of secondary effluent compared to the higher ozone requirements for non-nitrified secondary effluent to achieve high levels of disinfection.

8. To optimize the ozonation equipment selection, a generator and contactor mapping procedure, similar to that presented should be employed to evaluate the effects of carrier gas ozone concentration and carrier gas flow rate.

SECTION 4

MATERIALS AND METHODS

PILOT FACILITY

Secondary and nitrified effluents from the Marlborough Easterly Advanced Wastewater Treatment Plant at Marlborough, Massachusetts, served as the sources of wastewater for this high level disinfection research study with ozone. The wastewater entering the plant, designed for a 0.24 m^3/s (5.5 mgd) average daily flow, is primarily of municipal origin. The treatment plant employs the following unit operations: comminution, grit removal, primary settling, two-stage activated sludge, chemical addition in the first activated sludge stage for precipitation of phosphorus, chlorine disinfection, reaeration, and vacuum filtration with sludge disposal to an on-site sanitary landfill (Figure 1). The research pilot facility was located in the secondary gallery of the treatment plant.

The pilot facility was designed to operate either at a steady wastewater flow rate or according to diurnal flow characteristics. Diurnal pilot facility flow rates were obtained automatically in proportion to the full Marlborough Easterly wastewater flow rate.

The average flow rate to the pilot facility was 2.5 l/s (40 gpm) and minimum and maximum flow rates were 1.0 l/s (16 gpm) and 4.4 l/s (70 gpm), respectively. A schematic of the ozone research pilot facility is presented in Figure 2. The Marlborough Easterly secondary or nitrified effluents prior to chlorination were pumped with a 2.2 kw (3 hp) Worthington centrifugal pump directly to the ozone contactors or filtered through two pressure filters each with a surface area of 0.46 m^2 (4.9 sq ft). The filter media contained both anthracite coal and sand. The filters were backwashed with the Easterly plant chlorinated final effluent flushing water system. The majority of the operational experiments were conducted with the filters in operation to reduce and control the suspended solids, providing consistent effluent qualities for comparative testing. The filtered effluent flowed by gravity to two ozone contactors which were piped for either parallel flow testing or series flow testing from contactor one to contactor two.

The ozonated contactor effluent flowed by gravity to a plant dewatering wet well where it was pumped to the primary settling

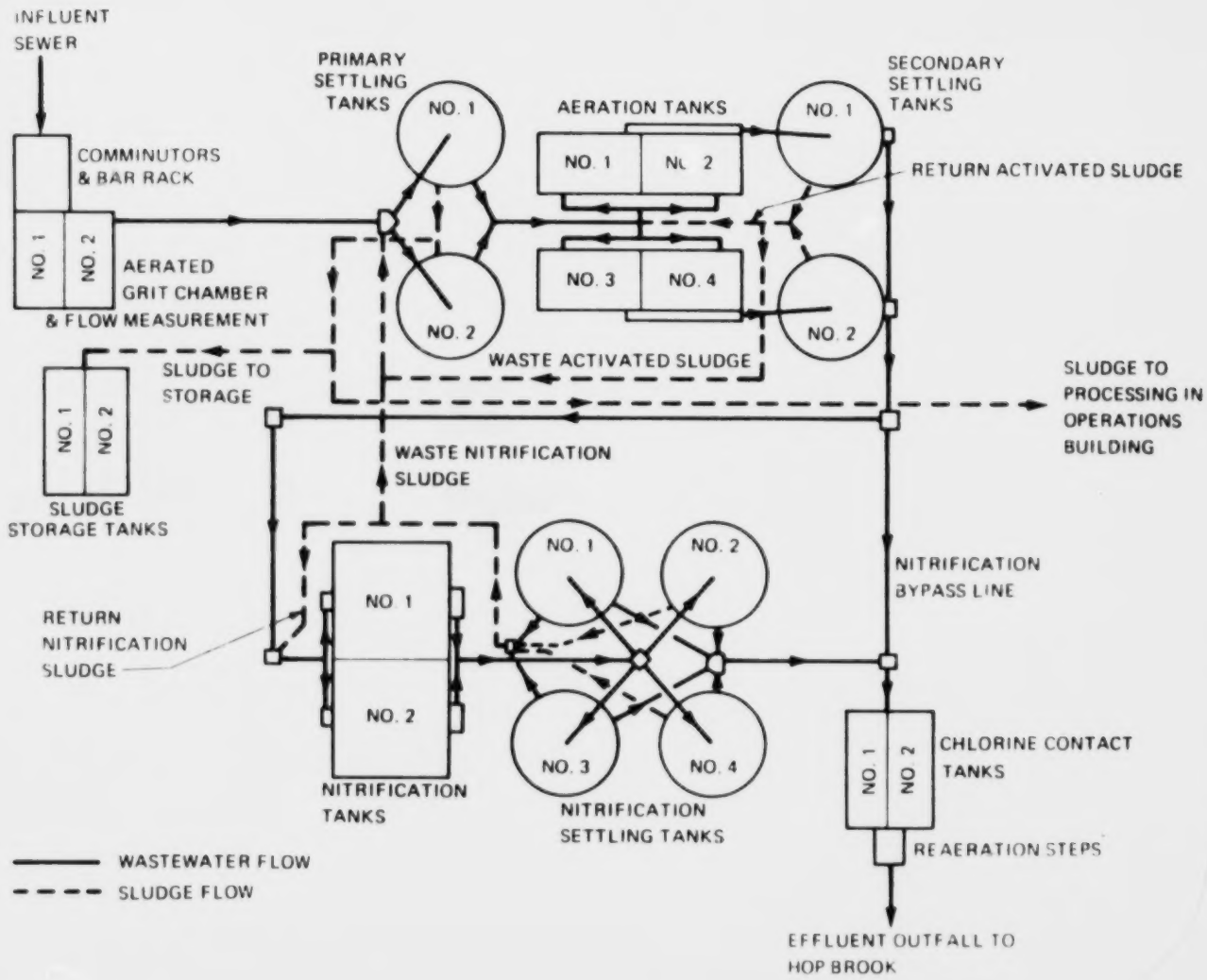

Figure 1. Marlborough wastewater treatment plant flow diagram.

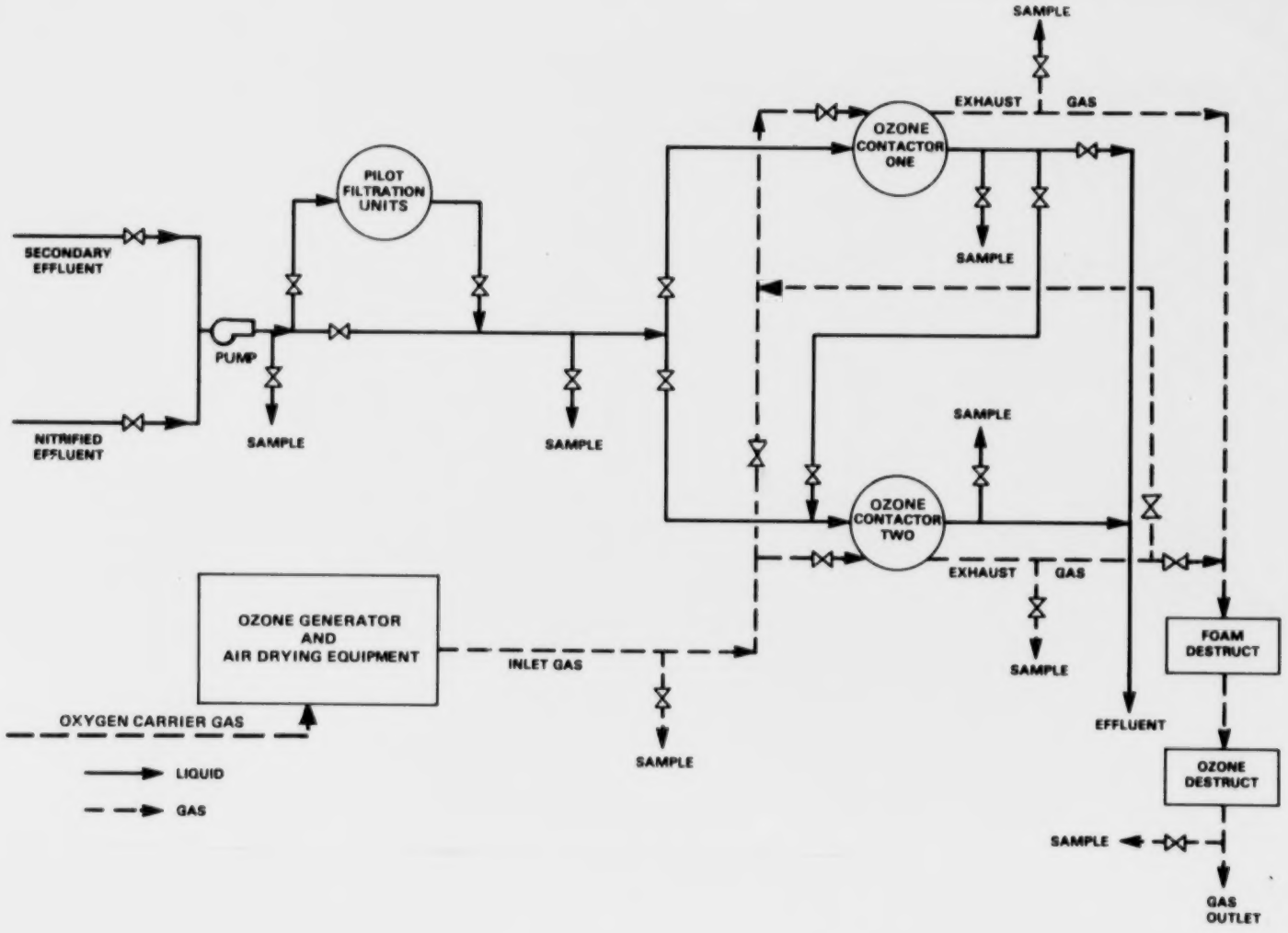

Figure 2. Schematic of pilot ozonation facility at Marlborough, Massachusetts.

tanks through the plant's secondary dewatering system. The other pilot plant liquid streams, such as filter backwash water and the foam destruct unit drainage, were also pumped to the primary clarifiers. During backwashing of the filters, wastewater flow to the contactors was interrupted due to the common filter backwash and contactor effluent drain piping.

Ozone was generated from air or oxygen feed gas with a Kerag generator Model TKC(s)-480. The generator had 210 generating tubes for a rated output of 480 g/h (24 lb/day) ozone at a 2 percent by weight ozone concentration with air carrier gas operation. The generator was water cooled and utilized 3,000 to 9,000 volts to generate ozone. To obtain these voltages, the 460 volt supply power first passed through a variable transformer which reduced the voltage to a 60 to 460 volt range. These voltages were then stepped up by a constant high voltage transformer, and the ozone output was proportional to the voltage. The ozone output was controlled by varying the voltage output of the variable transformer. This was accomplished either manually or by pacing the output voltage with the pilot plant flow at some constant applied dose. The applied dosage could be varied as desired.

When the generator was operated with air carrier gas, room air was dried to a dew point near -50 ^{o}C. Two 230 kg silica gel driers were alternated during a 36-hour cycle, containing a maximum of 8 hours hot air regeneration and 28 hours cooling by conduction. Air filters were placed before the driers to keep dust particles out of the generator air carrier gas and after the driers to keep silica dust from entering the generator.

An outside liquid oxygen storage tank was installed near the pilot facility location to supply oxygen gas for oxygen carrier gas ozone generation. Liquid oxygen was stored at approximately 690 kN/m^2 (100 psi) and then vaporized through two pressure regulators to the gas phase at approximately 3.4 kN/m^2 (0.5 psi).

The Kerag generator operated under a slight vacuum (0.1 to 1.5 mm Hg, depending on gas flow rates) during air carrier gas operation because the carrier gas was drawn through the generator by creating a vacuum at the ozone contactors. This mode of drawing the gas through the generator necessitated delivery of oxygen at less than 6.9 kN/m^2 (1 psi) at the generator. The 2.2 kW (3 hp) contactor motors rotated immersed turbine like mixers at 3,400 rpm to create the necessary suction pressure to draw the ozonated gas through the generator and to mix the gas with the wastewater. During oxygen carrier gas operation, there was a slight positive pressure at the generator. The gas flow rates varied from 1.4 to 8.3 l/s through each contactor. Each contactor was designed oversize to carry the total pilot plant liquid flow of 4.4 l/s so that the maximum gas flow through the generator was 8.3 l/s. The gas and wastewater flow rates available provided a

minimum gas to liquid ratio of 0.32. Gas piping was arranged to provide flexibility in recycling all or a portion of the exhaust gas from either of the contactors to the other. The wastewater flow was operated in the series mode through the two contactors when the gas was recycled.

Exhaust gas from the contactors contained both ozone and foam. During the air carrier gas operation, the foam was destroyed by a two-point application of cold water spray in an external PVC foam destruct unit. The exhaust gas from both contactors was collected and passed through this unit. The ozone in the exhaust gas was thermally destroyed with an in-line gas heater that increased the gas temperature to a maximum of 400 ^{o}C.

During the oxygen carrier gas phase, the foam spray system was modified to spray directly into the exhaust gas pipe of each contactor. This modification eliminated the need for excess piping and an external foam destruct unit which would have been aluminum or stainless steel to be compatible with the oxygen/ozone gas mixture.

The basic design data of the ozone pilot facility are presented in Table 3.

SAMPLING AND ANALYTICAL TECHNIQUES

The majority of the liquid samples were grab samples collected on the influent and effluent lines of each contactor through valved sampling ports. The liquid sample lines were flushed for about 30 seconds prior to each grab sample collection to assure collection of a representative sample. During the 5-day, continuous operation periods of the Reliability Phase, 24-hour flow proportioned composite samples were collected, as well as the normal grab samples. Throughout the study, coliform analyses were performed on grab samples.

Liquid samples were analyzed according to the procedures outlined in "Standard Methods for the Examination of Water and Wastewater" (10). Bacteriological analyses for total coliforms were conducted by the standard Membrane Filtration (MF) method according to the procedures in Standard Methods (10), since results by Meckes and Venosa (18) indicated no significant difference between the MF and the MPN techniques for enumerating total coliform bacteria in secondary effluent disinfected with ozone. All liquid samples collected for bacteriological analysis were neutralized with sodium thiosulfate to destroy residual ozone. A modification of the amperometric titration method for total residual chlorine was employed for determination of total residual oxidants (19). A Delta Scientific Continuous Automatic ozone monitor controller, (Model 8340) was also used to determine post-disinfection ozone levels. Monitoring was performed

TABLE 3. BASIC DESIGN DATA

Item	Description
Wastewater Flows	
Marlborough Easterly	
Average	0.12 m^3/s (2.76 mgd)
Minimum	0.02 m^3/s (0.50 mgd)
Maximum	0.33 m^3/s (7.50 mgd)
Pilot Facility	
Average	2.5 l/s (40 gpm)
Minimum	1.0 l/s (16 gpm)
Maximum	4.4 l/s (70 gpm)

Ozone Application Rates, g/h	Applied ozone dosage, mg/l			
Effluent Flow	10	15	20	30
2.5 l/s	90	135	180	270
1.0 l/s	36	54	72	108
4.4 l/s	156	234	312	468

Ozone Generator	
Type	Kerag Model TKC (S)-480
Max. output at 2.0 percent by wt.	
g/h	480
lb/day	24
Operating voltage	3-phase, 460-V, 60-Hz
Control voltage	112-V, 60-Hz
Number of generating tubes	210
Cooling water	
Maximum temperature	14 ^{o}C
Air Dryers	
Silica gel each drier	

TABLE 3 (Continued)

Item	Description	
Type	3-6 mm Diamantgel Type E	
Weight	230 kg	
Regeneration		
Cycle times		
Total	36 h	
Regeneration maximum	8 h	
Cooling	28 h	
Temperature range	120-270 °C	
Air quantity	38 l/s	
Drier power	3.5 kW	
Contactor		
Type	Kerag, Type RB 110/280	
Power	2.6 kW	
Size	2.2 kW (3 hp)	
Liquid volume, m^3	0.32	
Detention time, min	One contactor	Two series contactors
At 2.5 l/s, average flow	2.1	4.3
At 1.0 l/s, minimum flow	5.3	10.6
At 4.4 l/s, maximum flow	1.2	2.4
Ozone destruct unit		
Type	Thermal	
Power	4.5 kW	
Maximum flow rate, l/s	9.6	
Pilot Filtration Equipment		
Model	Baker Filtration Company Model HRC-330	

TABLE 3 (Continued)

Item	Description
Type	Pressure
Filter media	Coal-sand
Filter bed dimensions	0.76 m diam. x 0.91 m deep
Filter area, m^2	Each 0.46 Total 0.91
Hydraulic loading	
Average	237 $m^3/m^2.d$
Minimum	95 $m^3/m^2.d$
Maximum	411 $m^3/m^2.d$

continuously during the latter stages of the study with the immersed Delta Scientific probe that is specific for dissolved ozone. The ozone residual value is less than the total residual oxidants value determined amperometrically because the latter includes other oxidizing agents such as hydrogen peroxide formed during ozonation.

Ozone concentration in the inlet and exhaust gas was determined iodometrically by the method of Birdsall, Jenkins, and Spadinger (20), and gas volumes were measured by a wet test meter. Prior to gas sample collection the gas lines were purged for approximately one minute to insure equilibrium conditions. Continuous measurement of ozone in the influent gas stream was made before and after collection of the grab sample for titration to provide assurance of a steady-state ozone concentration. Continuous ozone monitoring was accomplished with a Dasibi Environmental Corporation ozone analyzer (Model 1003-HC) that was recalibrated at the beginning of each day of investigation. The ozone level in the ambient air of the pilot facility located within the secondary gallery was monitored by a MAST Model 724-5 (AL) (Mast Development Company). The ambient levels were generally below 0.01 mg/l. The dew point of the dried ozonator air carrier gas was monitored daily with an Alnor Dew Pointer (Model 7300, Alnor Instrument Company).

PILOT FACILITY OPERATION SCHEDULE

Preliminary Evaluation Phase

This 15-week phase was performed during the period of mid-November 1978 to mid-January 1979. A total of 10 ozonation disinfection experiments was performed on secondary effluent, 28 disinfection experiments on filtered secondary effluent, and 51 disinfection experiments on nitrified effluent. The number of disinfection experiments does not reflect the magnitude of the data base, due to multiple data points generated from each experiment (in all phases).

Correlation Phase

This 20-week phase was performed during the period of late February 1979 through mid-July 1979. Four biologicaly treated effluent types were investigated; 48 disinfection experiments on secondary effluent, 137 disinfection experiments on filtered secondary effluent, 68 disinfection experiments on nitrified effluent, and 46 disinfection experiments on filtered nitrified effluent.

Reliability Phase

This phase lasted 16 weeks, covering the period of late July to early November 1979. A total of 105 disinfection experiments on filtered secondary effluent and 108 disinfection experiments on filtered nitrified effluent were performed.

A total of 48 disinfection experiments were performed during the filtered nitrified continuous testing period which occurred from 12:00 noon on Saturday, October 20, 1979 through 4:00 a.m. on Wednesday, October 24, 1979. A total of 50 disinfection experiments was performed during the filtered secondary continuous testing period which occurred from 6:00 a.m. on Wednesday, November 7, 1979 through 6:00 a.m. on Monday, November 12, 1979.

Oxygen Evaluation Phase

This phase was performed during the period ranging from February to June 1980. A total of 38 filtered secondary disinfection experiments and 48 filtered nitrified disinfection experiments were conducted.

Ozone Generator and Contactor Mapping

In order to evaluate the economics of ozone disinfection, as defined in the study objectives, a detailed evaluation of the pilot facility ozone generator and gas-liquid contactors was required. This task was accomplished by mapping the ozone generator and contacting equipment. Mapping consisted of a process

where the specified performance parameters were monitored and quantified over the range of operational variables.

The ozone generator was mapped by monitoring the ozone production and power consumption over the available gas flow rates and applied voltage with both air and oxygen carrier gases. Power was monitored directly in terms of kilowatts with a Westinghouse Industrial Analyzer, Type TA, calibrated to a tolerance of 2 percent. Measurements were taken at the input lines of the high voltage transformer. Therefore, these measurements reflect only the power to generate ozone and include only inefficiencies of the generator and the high voltage transformer. No other power requirements, such as air drying (for air carrier gas) or contacting, were included in the generator mapping measurements. The ozone production was monitored in terms of grams per hour and grams per cubic meter gas concentration.

Exclusion of the other power requirements was necessary to provide a basis for the evaluation of ozone generation with air or oxygen carrier gas. The remaining components of the pilot facility: air drying equipment, ozone contactors, and thermal destruct unit, were monitored separately with the same Industrial Analyzer. These additional power measurements were necessary to determine the total power requirements for the total ozonation system.

The generator was initially mapped in late March 1979 using air carrier gas. A second air mapping program was conducted in late September 1979 to evaluate output variability and normal wear on the equipment. The oxygen generator mapping was conducted in early February 1980.

The contactors were also mapped to determine the ozone transfer efficiency with both air and oxygen carrier gases. Transfer efficiencies were determined on both filtered secondary and filtered nitrified effluents. Both contactors were employed in the series operation mode with gas flow countercurrent to effluent flow during the mapping investigations.

Contactor mapping was conducted to collect data over a range of applied ozone doses at constant effluent flow rates and water quality. Data for each constant applied dose series was obtained by varying the gas flow rate and the ozone concentration. The range of applied doses investigated was determined to be that required to obtain levels of disinfection ranging from approximately 1,000 total coliforms per 100 ml to 2.2 total coliforms per 100 ml for both effluent types.

The air contactor mapping experiments were performed in late August and early September 1979. The oxygen contactor mapping experiments were performed in late February and early March 1980. Contactor transfer efficiency was also routinely determined with

each experimental run throughout the entire test period. This monitoring effort provided sufficient data to evaluate contactor performance variability.

DATA ANALYSIS

During the pilot plant facility operation, over 600 separate experiments were performed. A single experiment consisted of 15 operational parameters, 7 performance parameters and at least 11 water quality parameters that were routinely monitored. A Digital Equipment Corporation computer system, Model PDP 11/70, was employed to assist in the handling of the large amount of data generated.

The computer capabilities were employed to store and segregate raw data files, check basic computations performed manually during the pilot facility operation and to assist with the data analysis. The computer data analysis capabilities were also utilized in the determination of grouped data file mean and standard deviation values, linear regression analysis, standard "t" test analysis and computer graphing.

FUNDAMENTAL DEFINITIONS

Fundamental definitions of applied ozone dose, percent ozone transfer efficiency, and absorbed ozone are presented below to assist in the understanding of the following discussions:

Applied Ozone Dose

$$D = Y_1 \ (Q_{gas}/Q_{liq})$$

where D = applied ozone dose, mg O_3/l_{liq}

Y_1 = concentration of ozone in the carrier gas, mg O_3/l_{gas}

Q_{gas} = carrier gas flow rate, l_{gas}/s

Q_{liq} = liquid flow rate, l_{liq}/s

Ozone Transfer Efficiency (TE)

$$\% \ TE = \frac{[Y_1 - Y_2]}{[Y_1]} \ 100$$

where % TE = percent ozone transfer efficiency

Y_2 = concentration of ozone in the exhaust gas leaving the contactor, mg O_3/lgas

Absorbed Ozone

$$A = D \times TE$$

$$A = Y_1 \ (Q_{gas}/Q_{liq}) \ \frac{[Y_1 - Y_2]}{[Y_1]}$$

$$A = (G_{gas}/Q_{liq}) \ (Y_1 - Y_2)$$

where A = actual ozone utilized or absorbed ozone concentration, mg O_3/l_{liq}

Ozone Production (OP)

$$OP = Y_1 \times Q_{gas}$$

where OP = ozone produced, mg O_3/s

SECTION 5

RESULTS

WATER QUALITY EVALUATIONS - AIR OPERATION

Ozone disinfection experiments were conducted with nitrified, filtered nitrified, secondary, and filtered secondary effluents by employing varying operating conditions to evaluate the ozone requirements to achieve high level wastewater disinfection during air carrier gas operation. The quality of these wastewater effluents prior to disinfection and the ozonated effluents were regularly monitored for total coliforms, COD, TSS, turbidity, temperature and pH. Other parameters, such as fecal coliforms, BOD, TOC, TKN, NH_3-N, NO_2-N, NO_3-N, color, and iron were also monitored on a routine basis.

Summaries of the primary water quality characteristics of the four effluents are presented in Tables 4 and 5. Due to the low suspended solids and turbidity measurements in the unfiltered nitrified effluent and the similar levels of COD in unfiltered and filtered effluents, the latter appear to be basically of the same water quality with the exception of total coliforms. The unfiltered and filtered secondary effluents also appear to be the same water quality. These assumptions were analyzed by student's t test for determination of significant differences between the mean values at the 99 percent confidence level.

When nitrified effluent was compared to filtered nitrified effluent, the TSS, turbidity and log total coliforms were significantly different. When comparing secondary to filtered secondary, TSS was the only parameter that appeared significantly different at the 99 percent confidence level. Due to the low values of TSS and turbidity observed in all effluents and the precision and accuracy of the analytical test methods employed at these low values, the means of these parameters were judged not to be signficantly different for the purpose of these investigations. Therefore, the water qualities for the nitrified and filtered nitrified effluents were combined to be indicative of filtered nitrified effluent, and the water qualities for the secondary and filtered secondary effluents were combined to be indicative of filtered secondary effluent, as shown in Table 6. The mean values of these two sets of combined water qualities were then evaluated for a significant difference. The influent COD values, NH_3-N values, and log total coliforms were found to be significantly

TABLE 4. SUMMARY OF NITRIFIED EFFLUENT CHARACTERISTICS PRIOR TO OZONATION

Parameter	Mean	Standard deviation	Minimum	Maximum
Filtered nitrified:				
TSS, mg/l	2.5	1.5	0.7	6.8
Turbidity, NTU	1.9	0.7	1.0	2.9
COD, mg/l	20.5	2.1	16.0	24.4
pH	-	-	6.4	7.5
Temperature, ^{o}C	7.2	-	5.5	8.5
Log_{10} total coliforms/100 ml	4.0	0.6	3.2	5.7
Nitrified:				
TSS, mg/l	5.7	1.8	3.3	10.0
Turbidity, NTU	3.2	0.8	1.8	5.1
COD, mg/l	21.7	2.6	16.1	25.7
pH	-	-	6.3	7.2
Temperature, ^{o}C	10.7	-	5.5	15.0
Log_{10} total coliforms/100 ml	4.7	0.5	3.9	5.5

TABLE 5. SUMMARY OF SECONDARY EFFLUENT CHARACTERISTICS PRIOR TO OZONATION

Parameter	Mean	Standard deviation	Minimum	Maximum
Filtered secondary:				
TSS, mg/l	3.6	1.9	1.6	8.0
Turbidity, NTU	3.9	2.4	1.4	12.0
COD, mg/l	39.2	6.8	21.0	49.6
pH	-	-	6.9	7.9
Temperature, ^{o}C	13.8	-	6.0	21.0
Log_{10} total coliforms/100 ml	5.6	0.6	4.5	6.4
Secondary:				
TSS, mg/l	6.3	5.0	2.2	16.4
Turbidity, NTU	4.7	1.7	3.4	8.7
COD, mg/l	40.4	5.8	32.5	52.4
pH	-	-	7.1	7.5
Temperature, ^{o}C	11.0	-	9.0	12.0
Log_{10} total coliforms/100 ml	5.5	0.2	5.0	5.8

TABLE 6. SUMMARY OF COMBINED EFFLUENT CHARACTERISTICS PRIOR TO OZONATION

Parameter	Mean	Standard deviation	Minimum	Maximum
Filtered nitrified:*				
TSS, mg/l	4.5	2.3	0.7	10.0
Turbidity, NTU	2.7	1.0	1.0	5.1
COD, mg/l	21.2	2.5	16.0	25.7
pH	-	-	6.3	7.5
Temperature, ^{o}C	9.4	-	5.5	15.0
Log_{10} total coliforms/100 ml	4.4	0.6	3.2	5.7
TOC, mg/l	19.5	-	5	35
TKN, mg/l	1.5	-	1.2	1.8
NH_3-N, mg/l	0.42	-	0.03	1.2
NO_2-N, mg/l	.01	-	-	-
NO_3-N, mg/l	6.9	-	-	-
Color, Pt-Co	20	-	10	30
Filtered secondary:+				
TSS, mg/l	4.8	3.8	1.6	16.4
Turbidity, NTU	4.2	2.2	1.4	12.0
COD, mg/l	39.7	6.4	21.0	52.4
pH	-	-	6.9	7.9
Temperature, ^{o}C	13.0	-	6.0	21.0
Log_{10} total coliforms/100 ml	5.4	0.5	4.5	6.4
TOC, mg/l	20	-	10	40

TABLE 6 (Continued)

Parameter	Mean	Standard deviation	Minimum	Maximum
TKN, mg/l	33.5	-	21	52
NH_3-N, mg/l	13.7	-	11.5	15.8
NO_2-N, mg/l	0.17	-	-	-
NO_3-N, mg/l	0.08	-	-	-
Color, Pt-Co	50	-	45	100

*Includes nitrified plus filtered nitrified.

+Includes secondary plus filtered secondary.

TABLE 7. ABSORBED OZONE AND TOTAL RESIDUAL OXIDANT REQUIREMENTS FOR DISINFECTION (FIGURES 4 AND 5)

Effluent type	Absorbed ozone, mg/l	Total residual oxidants, mg/l
High-Level Disinfection (less than 2.2 total coliforms/100 ml):		
Filtered Nitrified	15	7
Nitrified	19	8
Filtered Secondary and Secondary	36	7
70 Total Coliforms/100 ml:		
Filtered Nitrified	3	1
Nitrified	9	2
Filtered Secondary and Secondary	18	3

different ($p>0.01$). The mean COD values differed by almost 20 mg/l, and the log total coliforms differed by more than one order of magnitude. Additional parameters monitored for the two effluents indicated similar concentrations of Fe^{+2}, approximately 0.1 mg/l, and Fe^{+3} ranging from 0.1 to 0.4 mg/l.

During air carrier gas operation absorbed ozone concentrations ranging from approximately 2 to 35 mg/l were applied to these effluents at contactor hydraulic reaction times of one to ten minutes yielding total effluent residual oxidant concentrations of 0.4 to 8.0 mg/l and DO levels of 10 to 15 mg/l. The disinfection performance, as reflected by the ozonated effluent total coliform counts per 100 ml, was compared with the corresponding absorbed ozone concentration and total residual oxidants by comparing the data points from all the experiments conducted during the water quality evaluation phase of the project. The results of this analysis are presented in Figures 3, 4, and 5, where the lines of best fit, as determined by linear regression analysis, along with the equations of the lines and the correlation coefficients are shown. In Figure 3 the analysis of all the data points for filtered secondary effluent are shown for total coliforms versus absorbed ozone concentration. Plots and similar analysis as shown in Figure 3 were conducted for all the lines represented in Figures 4 and 5. The absorbed ozone and total residual oxidant concentrations corresponding to high level disinfection (less than 2.2 total coliforms per 100 ml) and to 70 total coliforms per 100 ml can be determined from these figures, as presented in Table 7. Fecal coliforms were never detected in the ozonated effluents at high level disinfection for total coliforms. Linear regression analysis of all the fecal coliform data (not presented) indicated 14 fecal coliforms per 100 ml could be achieved on filtered secondary effluent with approximately 15 mg/l absorbed ozone concentration and 3 mg/l total residual oxidants. These values are consistent with achieving 70 total coliforms per 100 ml with filtered seconary effluent (Table 7).

The filtered nitrified and nitrified effluents were initially analyzed separately (Figures 4 and 5) with respect to disinfection due to the significant difference between the initial total coliform counts (mean nitrified counts more than five times higher than filtered nitrified counts). However, since the two nitrified effluents investigated were essentially of the same chemical water quality, with the exception of the initial total coliform counts, the ozone requirements to achieve a certain log total coliform reduction would be expected to be the same for both effluents. This aspect of the disinfection performance can be demonstrated by plotting the log total coliform reduction (Log_{10} No/N; where No = initial number of total coliform bacteria, and N = the number remaining after disinfection) versus the log absorbed ozone concentration, as shown in Figure 6. The correlation coefficient of 0.76 for all the data points indicates the ozone requirements to achieve a specific log total coliform reduction to be similar for both effluents.

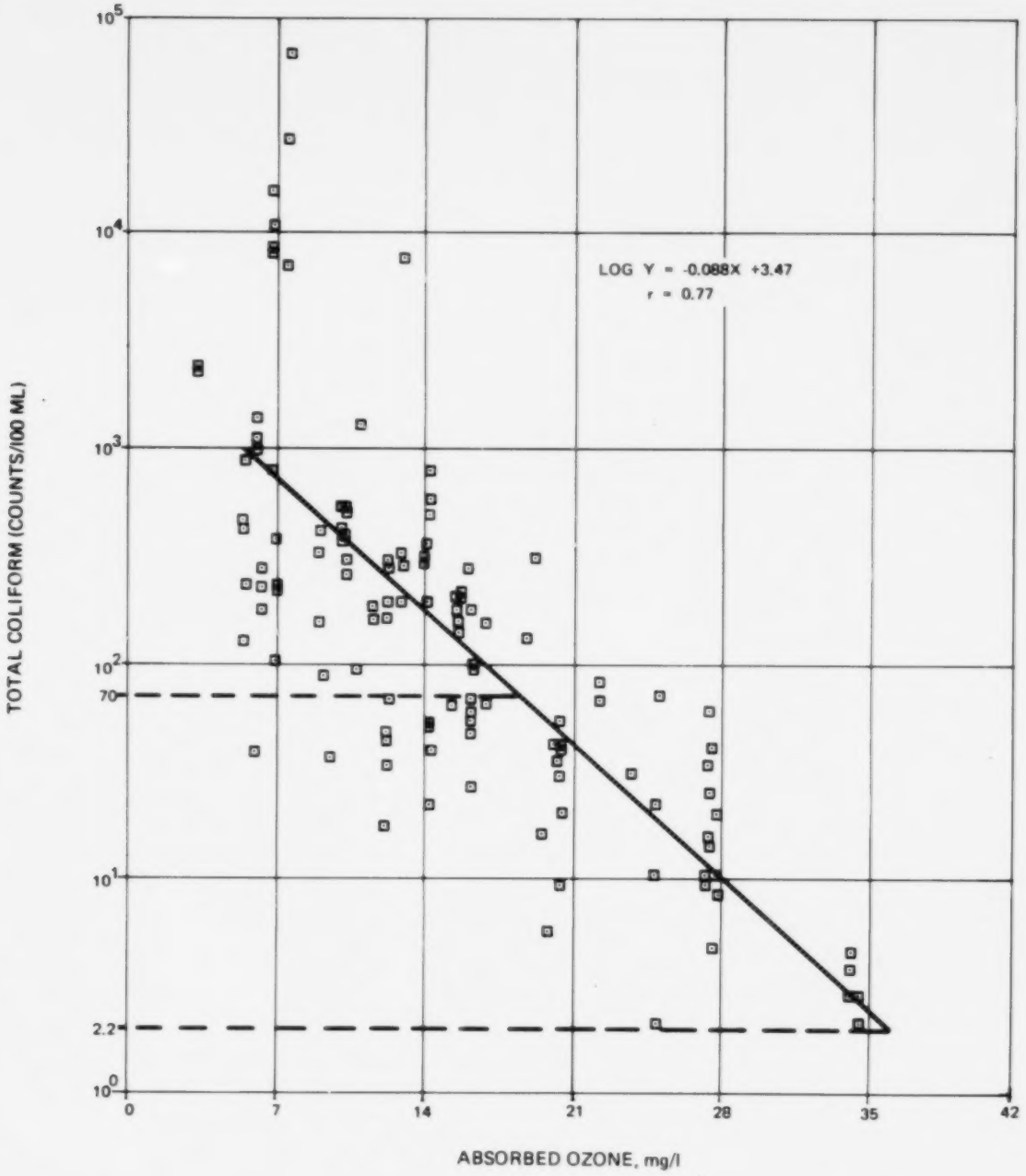

Figure 3. Total coliform density versus absorbed ozone concentration for filtered secondary effluent.

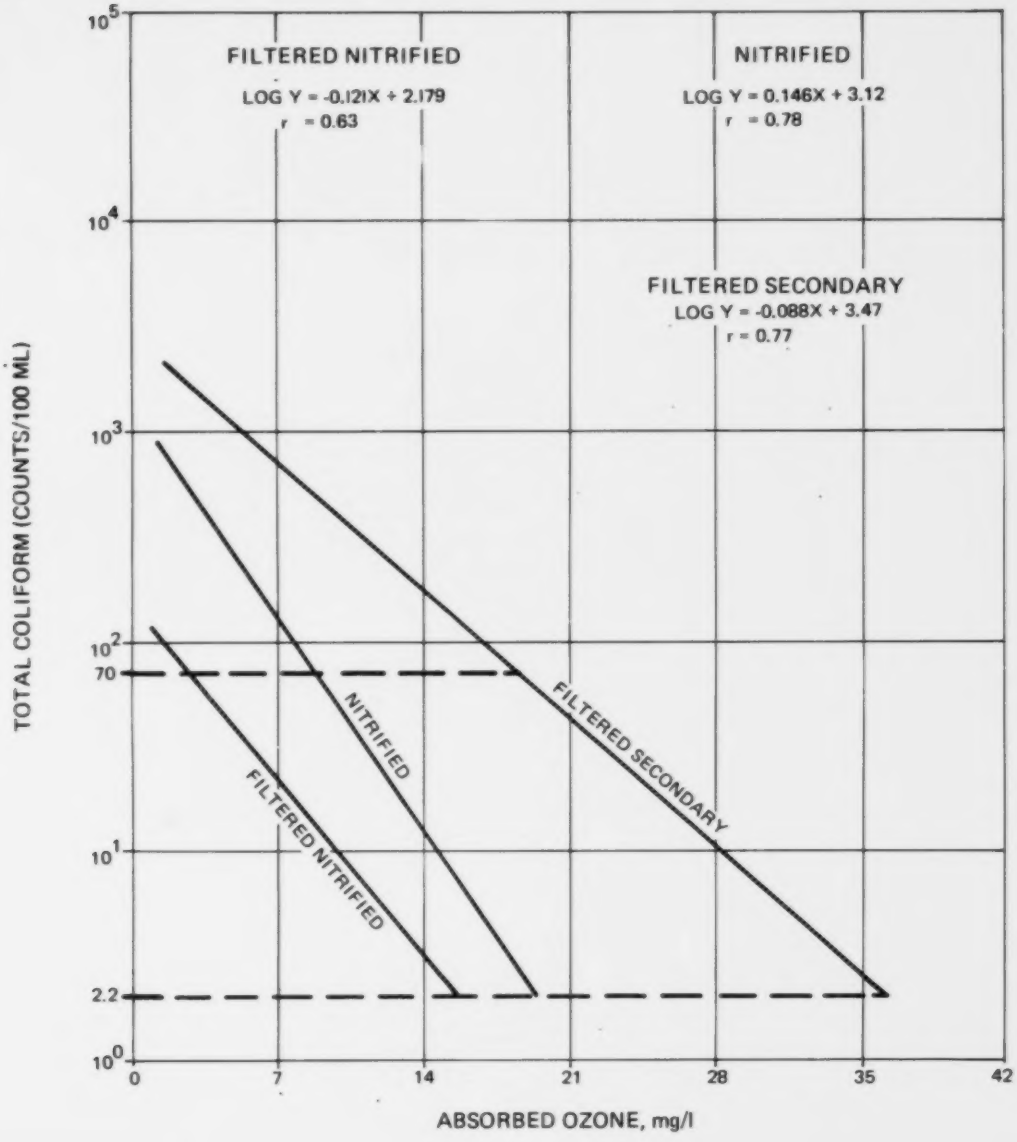

Figure 4. Total coliform density versus absorbed ozone concentration for various effluents.

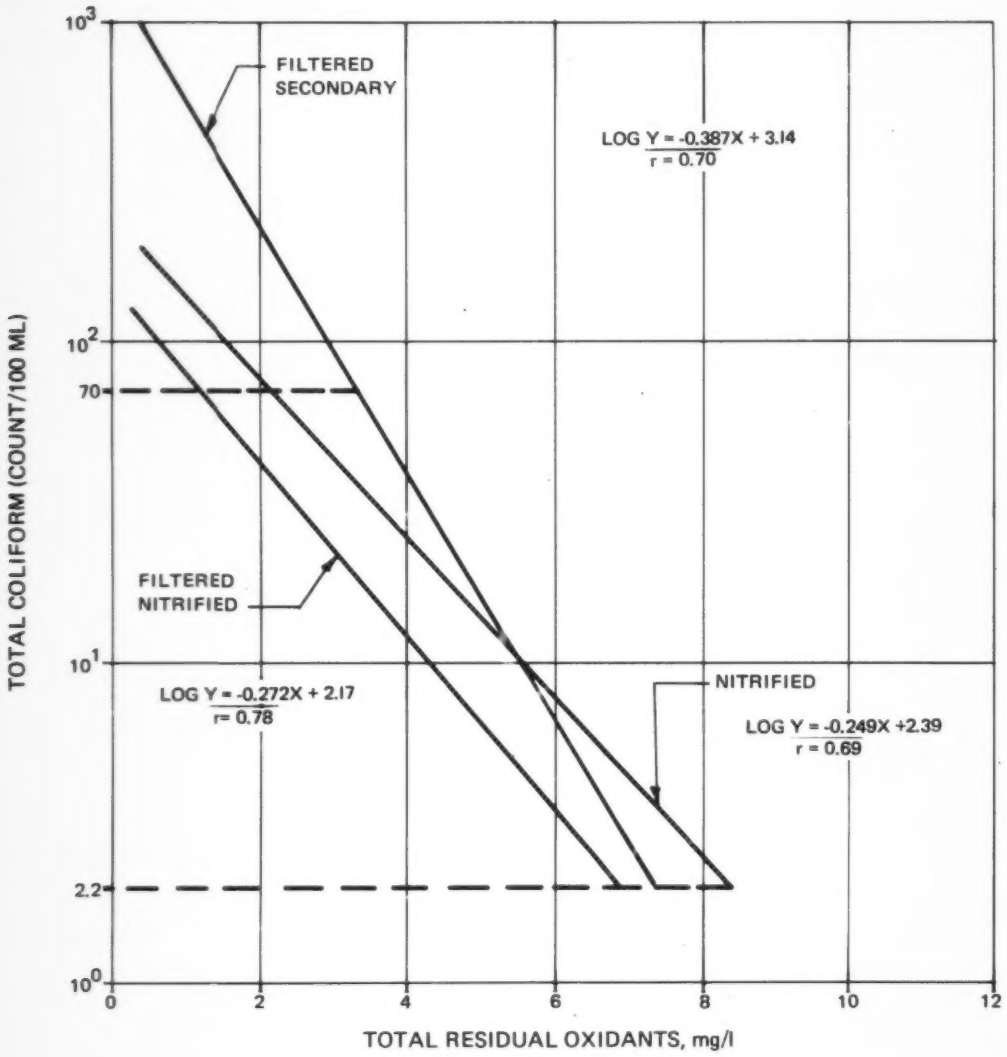

Figure 5. Total coliform density versus total residual oxidants concentration for various effluents.

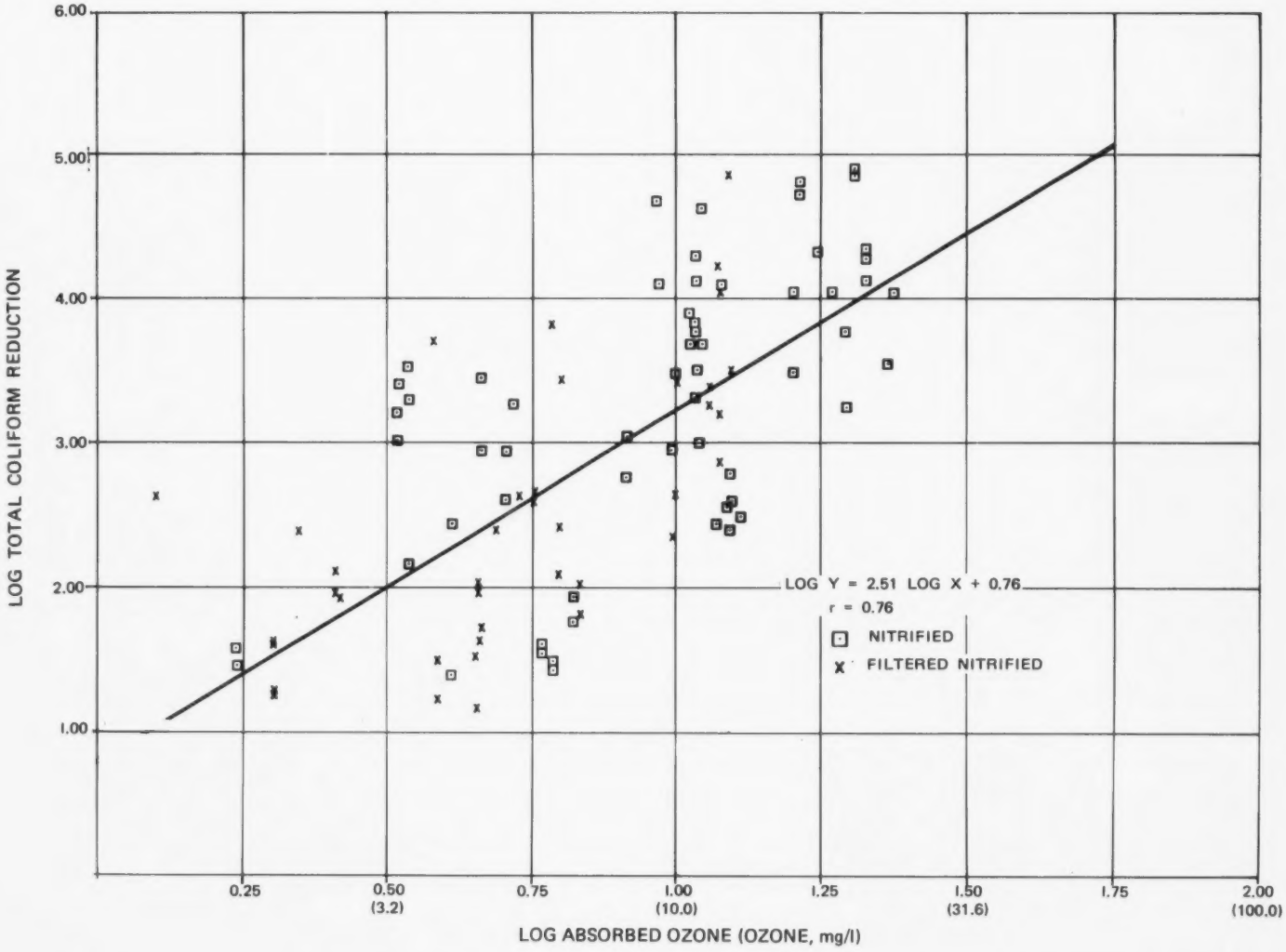

Figure 6. Log total coliform reduction versus log absorbed ozone concentration for nitrified effluents.

The log total coliform reduction as a function of log absorbed ozone for combined secondary and filtered secondary effluents is presented in Figure 7. The required absorbed ozone concentrations to achieve high level disinfection for the combined effluents can be calculated from Figures 6 and 7 by using the geometric mean influent log total coliform values listed in Table 6, as presented in Table 8.

TABLE 8. ABSORBED OZONE REQUIREMENTS FOR DISINFECTION (FIGURES 6 and 7)

Effluent type	Absorbed ozone, mg/l
High Level Disinfection (less than 2.2 total coliforms/100 ml):	
Filtered Nitrified	20
Filtered Secondary	42
70 Total Coliforms/100 ml:	
Filtered Nitrified	5
Filtered Secondary	14

As indicated in Figure 5, a total residual oxidant concentration of approximately 7 to 8 mg/l was required for both effluents to achieve less than 2.2 total coliforms per 100 ml. Since the previous data also indicated that total coliform reduction correlated well with both absorbed ozone and total residual oxidants, the residual oxidants would be expected to correlate with the absorbed ozone concentration. Total residual oxidant concentrations, as a function of absorbed ozone, for the combined water qualities are plotted in Figures 8, 9 and 10. The residual oxidants increased at a faster rate as ozone was absorbed in the nitrified effluent compared to the secondary effluent even though the ozone transfer efficiency was lower with nitrified effluent. Thus the total residual oxidants concentration for high level disinfection was achieved at a lower absorbed ozone concentration in nitrified effluent (Figure 10).

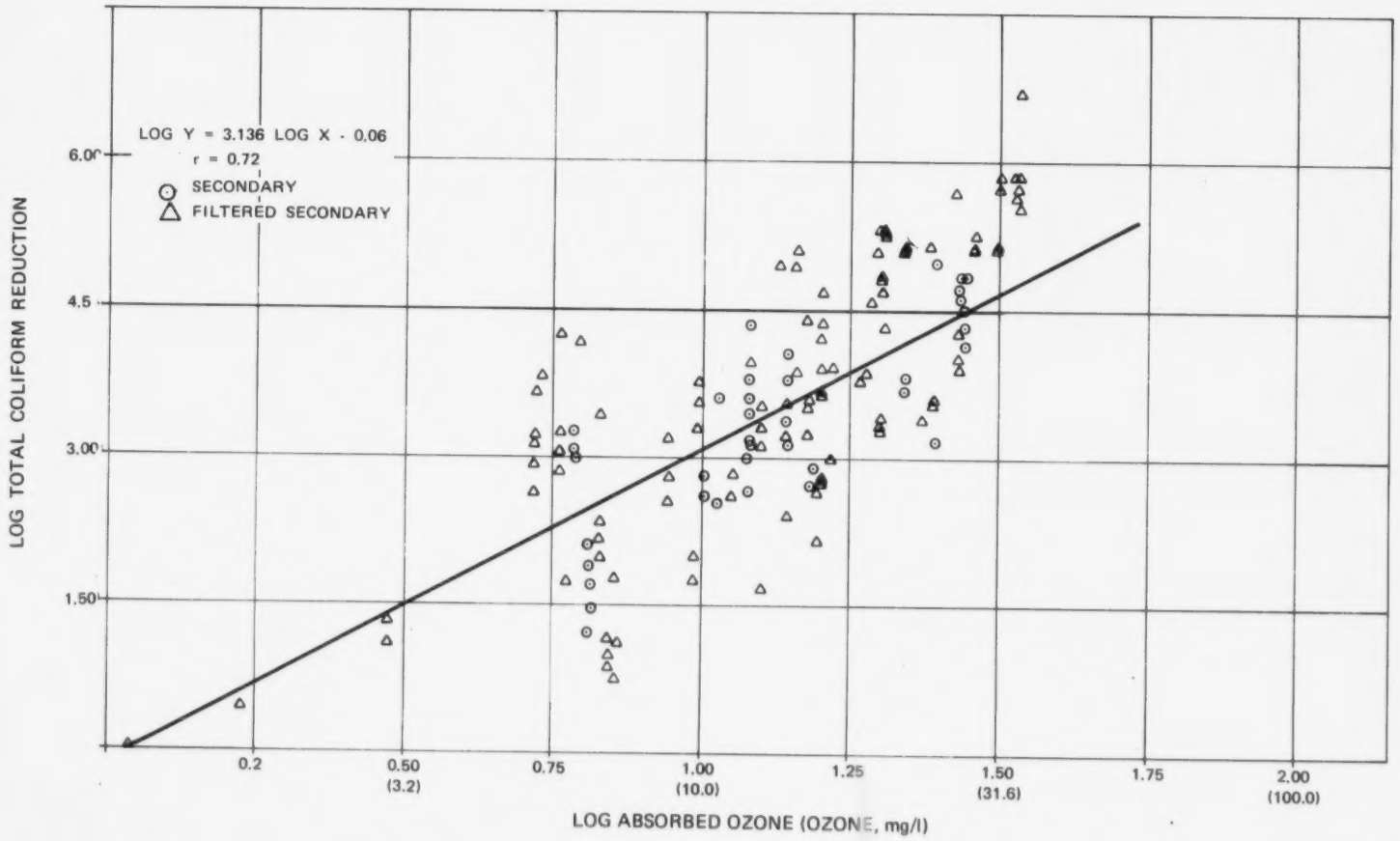

Figure 7. Log total coliform reduction versus log absorbed ozone concentration for secondary effluents.

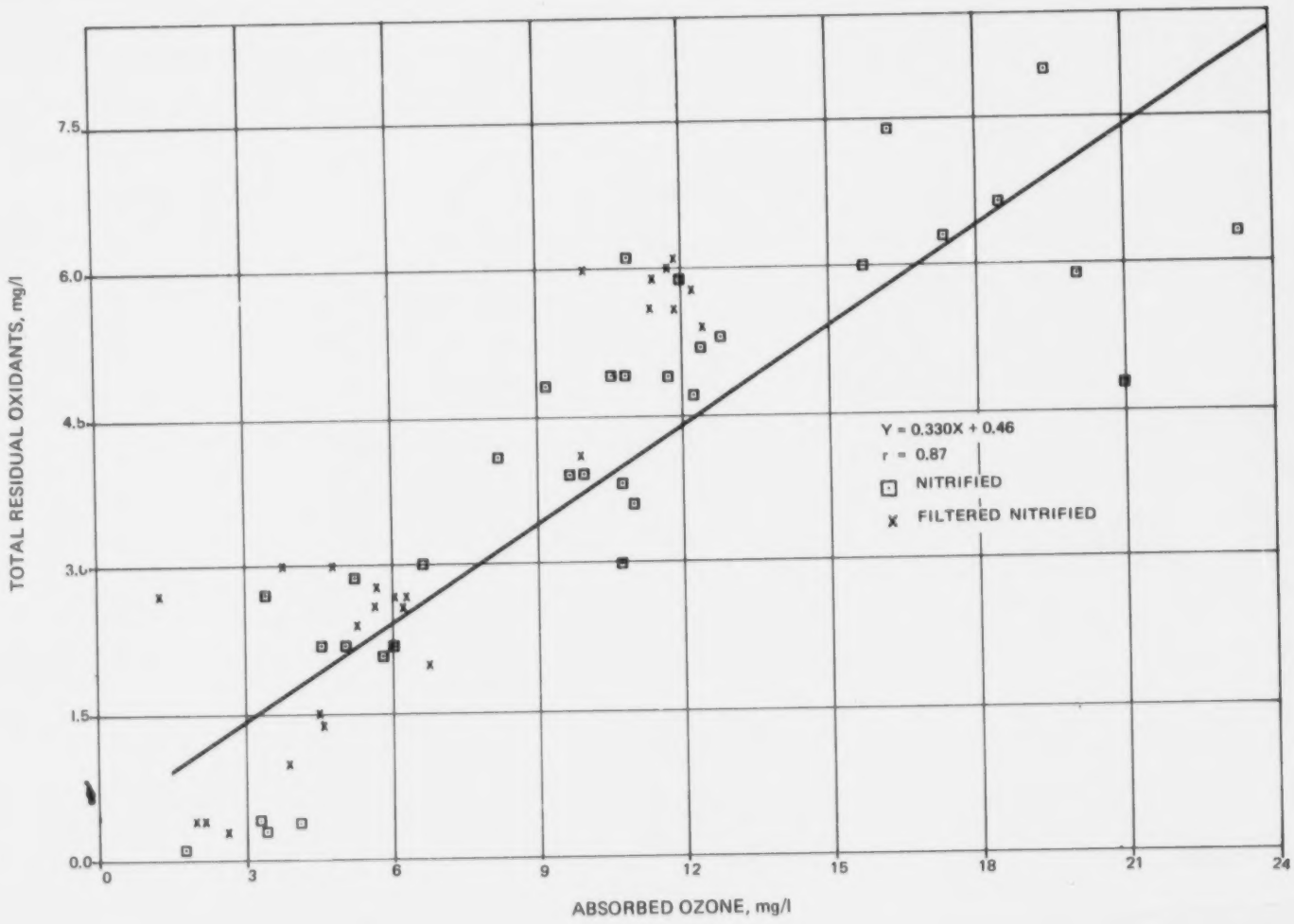

Figure 8. Total residual oxidants versus absorbed ozone concentration for nitrified effluents.

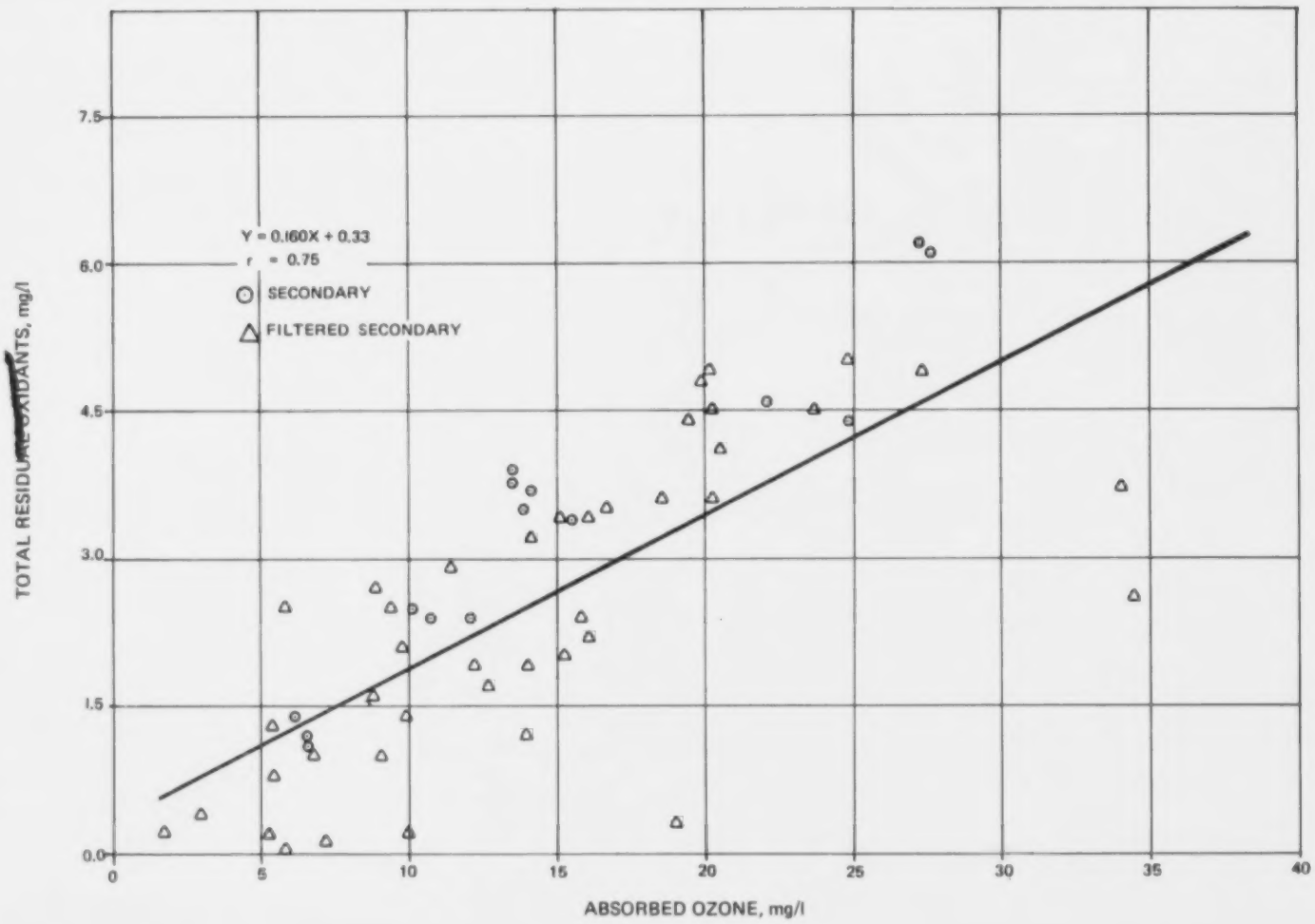

Figure 9. Total residual oxidants versus absorbed ozone concentration for secondary effluents.

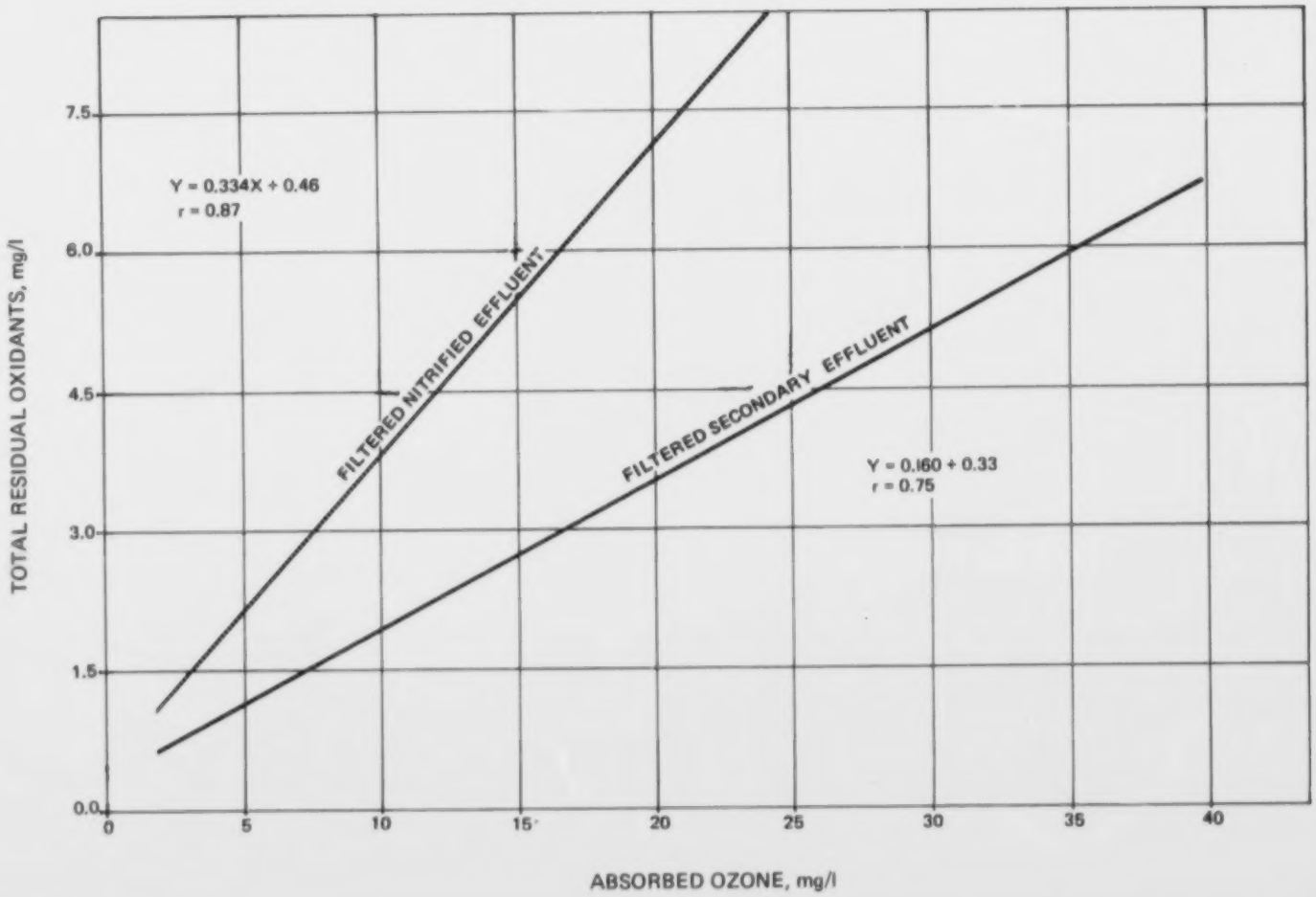

Figure 10. Total residual oxidants versus absorbed ozone concentration for filtered nitrified and filtered secondary effluents.

Due to the very good and consistent water qualities of the nitrified and secondary effluents, the filtered and unfiltered effluents were not found to be significantly different during this investigative period. After combining nitrified with filtered nitrified effluents and secondary with filtered secondary effluents, the two combined effluents were found to be significantly different with respect to COD, NH_3-N and initial total coliform counts. The required absorbed ozone concentrations to achieve comparable levels of disinfection were found to be higher with the secondary effluent quality.

During a short period in the summer months the wastewater temperature increased to the point where the kinetics of carbonaceous BOD removal were enhanced and partial nitrification occurred in the first stage of the treatment system. The resultant secondary effluent quality was temporarily improved and was similar to the nitrified effluent as shown in Table 9, and compared to Table 6. The NH_3-N data presented in Table 6 do not include experimental runs of this period. During this time period when the secondary effluent quality was comparable to the nitrified effluent quality, the required absorbed ozone concentrations to achieve high level disinfection were similar to those for nitrified effluent, as shown by the data points in Figure 11. Approximately 40 experiments were conducted during this time period. The number of experiments is not truly reflected in Figure 11 due to the overlap of data points, especially at high level disinfection.

TABLE 9. FILTERED SECONDARY EFFLUENT CHARACTERISTICS DURING PERIOD OF PARTIAL NITRIFICATION

Parameter	Mean	Standard deviation	Minimum	Maximum
COD, mg/l	26.6	1.8	22.8	29.2
TSS,mg/l	1.7	0.6	1.0	2.9
Turbidity, NTU	1.5	0.6	0.9	2.8
NH_3-N, mg/l	3.9		2.0	5.2
NO_2-N, mg/l	1.1	0.5	0.6	2.2

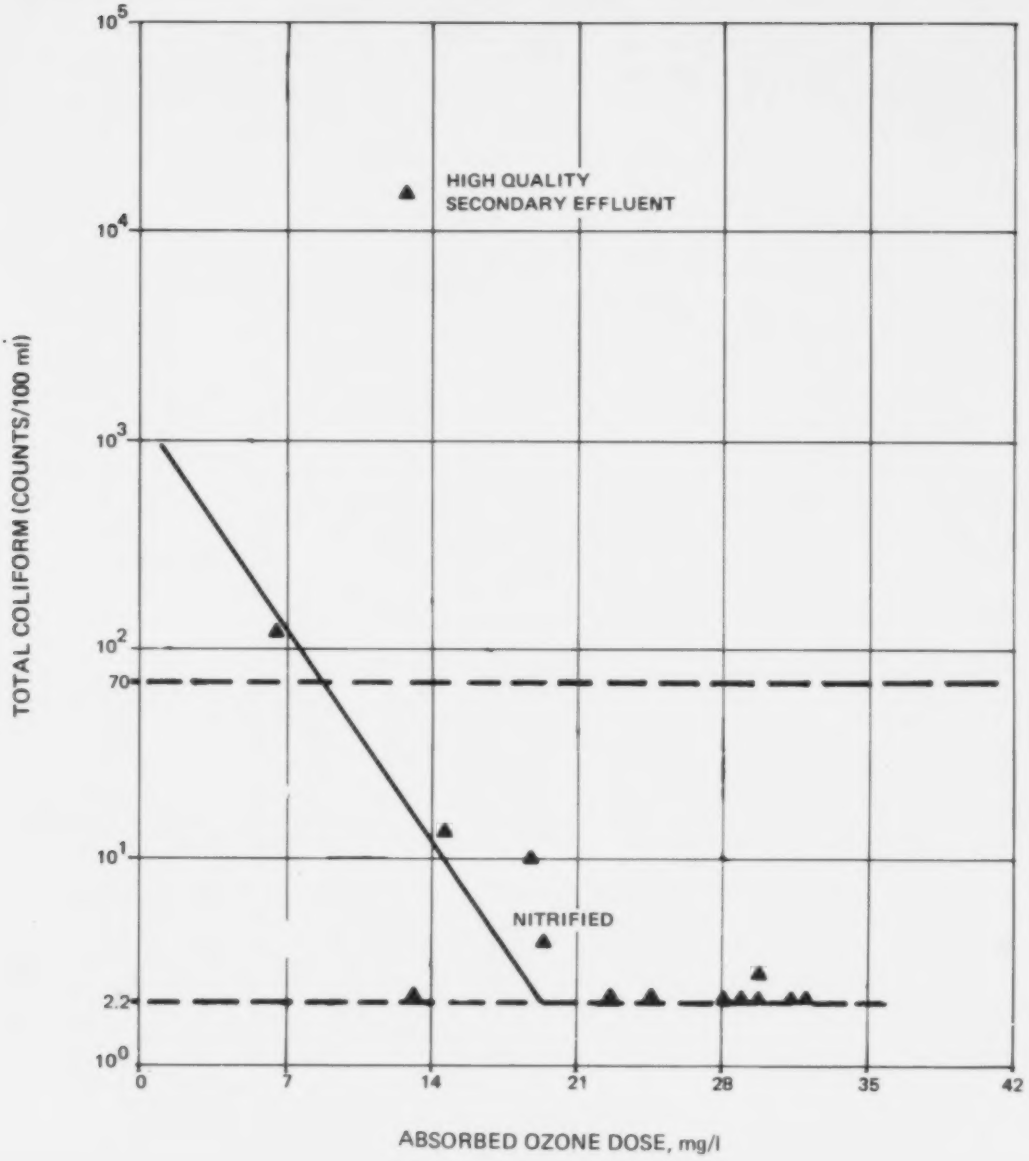

Figure 11. Total coliform density versus absorbed ozone concentration.

Reliability Phase Continuous Operation - Air Carrier Gas

Two five-day, continuous operations were performed to evaluate ozonation system disinfection reliability, process control and equipment reliability. Included in the operations were night time and weekend monitoring to evaluate low strength and low flow conditions. One continuous operating period was conducted to evaluate disinfection of filtered nitrified effluent to a high level of 2.2 total coliforms/100 ml. The second period was conducted to evaluate the disinfection of filtered secondary effluent to 70 total coliforms/100 ml. During both periods, ozone was generated from dried air carrier gas.

The water qualities prior to disinfection during the continuous operation periods are presented in Table 10 for the filtered nitrified and filtered secondary effluents.

TABLE 10. EFFLUENT CHARACTERISTICS DURING CONTINUOUS OPERATION PERIODS

Parameter	Mean	Standard deviation	Minimum	Maximum
Filtered Nitrified:				
TSS, mg/l	0.8	0.6	0.2	2.3
Turbidity, NTU	1.3	0.3	0.9	2.3
COD, mg/l	20.1	7.2	13.0	27.0
pH	-	-	6.7	7.4
Temperature, ^{o}C	16.7	-	15.5	17.5
Log_{10} total coliforms/100 ml	4.4	0.3	3.3	4.7
Filtered Secondary:				
TSS, mg/l	1.9	1.6	2.0	11.0
Turbidity, NTU	5.4	1.8	2.9	9.3
COD, mg/l	31.2	6.1	12.0	53.0
pH	-	-	6.4	7.9
Temperature, ^{o}C	14.9	-	14.5	15.5
Log_{10} total coliforms/100 ml	5.0	0.4	4.0	5.9

During the two continuous operation periods, the generator output was paced by effluent flow to maintain a constant applied dose. The maximum to minimum flow rates varied by a 4 to 1 ratio. The gas flow rate was varied manually to simulate an automatic gas flow regulation. A relatively constant absorbed dose was realized throughout the continuous operation periods.

High level (2.2 total coliforms per 100 ml) disinfection of filtered nitrified effluent was obtained in 40 of 48 samples taken with an applied dose of 30 mg/l (mean absorbed ozone concentration of 15 mg/l). With an applied dose of approximately 30 mg/l (mean absorbed ozone concentration of 20 mg/l) the geometric mean total coliform count per 100 ml was 22 in the ozonated filtered secondary effluent. Successful disinfection to the 70 total coliform level was achieved in 40 of 49 experiments.

WATER QUALITY EVALUATIONS - OXYGEN OPERATIONS

Ozone disinfection experiments were conducted with filtered nitrified and filtered secondary effluents by employing varying operating conditions to evaluate the ozone requirements to achieve high level disinfection with oxygen carrier gas. The primary purpose of these investigations was to confirm absorbed ozone and total residual oxidant requirements with oxygen compared to air carrier gas operation. The results of the water quality parameters monitored during these investigations are presented in Table 11.

TABLE 11. EFFLUENT CHARACTERISTICS DURING OXYGEN CARRIER GAS WATER QUALITY EVALUATIONS

Parameter	Mean	Standard deviation	Minimum	Maximum
Filtered Nitrified:				
TSS, mg/l	1.6	0.9	0.7	3.6
Turbidity, NTU	1.0	0.2	0.7	2.0
COD, mg/l	21.5	2.2	18.0	24.0
pH	-	-	6.8	7.5
Temperature, ^{o}C	17.0	-	14.5	20.0
Log_{10} total coliforms/100 ml	4.5	0.4	3.8	5.4
NH_3-N, mg/l	0.06	-	0.02	0.1
Filtered Secondary:				
TSS, mg/l	12.6	5.8	3.6	26.4
Turbidity, NTU	9.7	3.0	5.5	15.0
COD, mg/l	62.2	12.9	36.1	83.0
pH	-	-	6.9	7.3
Temperature, ^{o}C	8.3	-	5.5	9.5
Log_{10} total coliforms/100 ml	6.6	0.2	6.2	6.9
NH_3-N, mg/l	19.1	-	17.5	20.9

The disinfection performance, as reflected by the ozonated effluent total coliform counts per 100 ml, was then compared with the corresponding absorbed ozone and residual oxidants. The results of this analysis are presented graphically in Figures 12, 13 and 14, where the lines of best fit, as determined by linear regression analysis, along with the equations of the lines and the correlation coefficients are shown. In Figure 12 the analysis of all the data points for filtered secondary effluent are shown. Similar analysis was conducted for filtered nitrified effluent as presented in Figures 13 and 14. The absorbed ozone and residuals corresponding to less than 2.2 and 70 total coliforms per 100 ml as determined from these figures are presented in Table 12. The number of disinfection experiments conducted with oxygen carrier gas was significantly less than that conducted with air carrier gas; however, the required absorbed ozone and residuals for high level disinfection were determined to be essentially the same by comparison of Table 12 to Tables 7 and 8.

TABLE 12. ABSORBED OZONE AND TOTAL RESIDUAL OXIDANT REQUIREMENTS FOR DISINFECTION WITH OXYGEN CARRIER GAS (FIGURES 13 and 14)

Effluent type	Absorbed ozone, mg/l	Residual oxidants, mg/l
High Level Disinfection (Less than 2.2 total coliforms/100 ml):		
Filtered Nitrified	20	8
Filtered Secondary	37	9
70 Total Coliforms/100 ml:		
Filtered Nitrified	3	1
Filtered Secondary	10	2

Total residual oxidant concentrations as a function of absorbed ozone concentration for filtered nitrified and filtered secondary effluents are presented in Figures 15 and 16, respectively. Results were similar to those obtained with air carrier gas operation (Figure 17 compared to Figure 10). The residual increased at a faster rate as ozone was absorbed in the nitrified

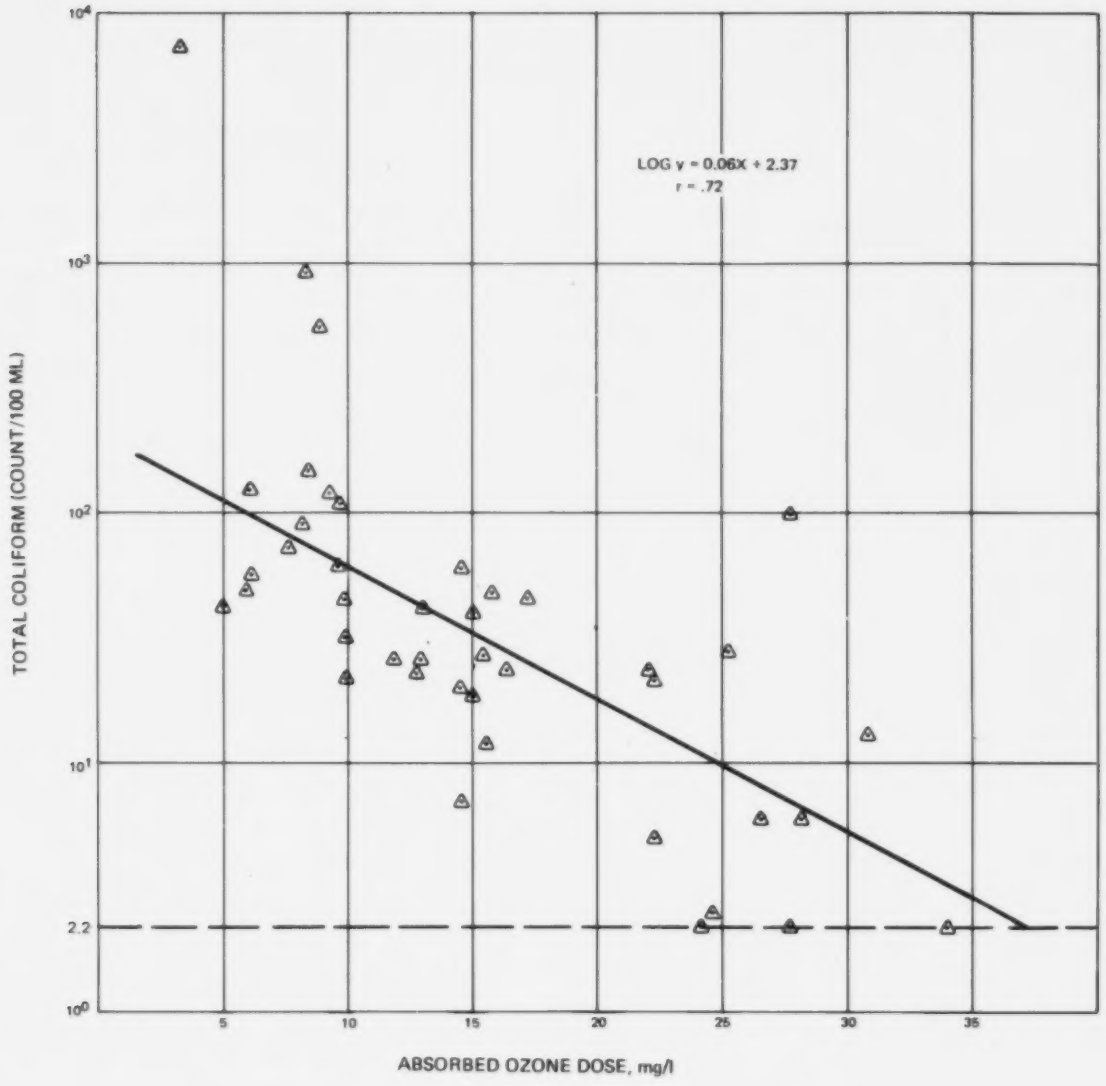

Figure 12. Total coliform density versus absorbed ozone concentration for filtered secondary effluent using oxygen carrier gas.

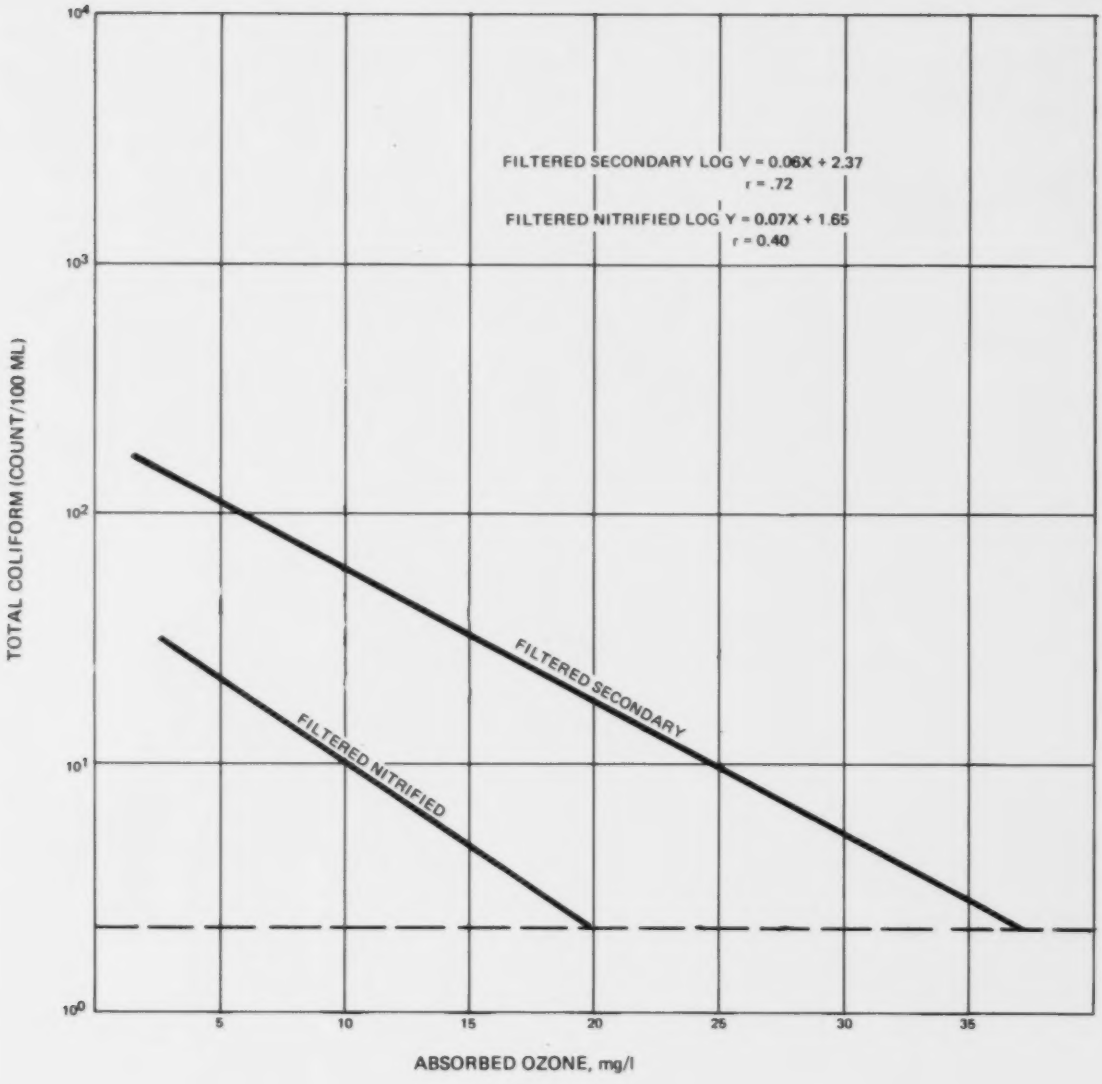
FILTERED SECONDARY LOG Y = 0.06X + 2.37
r = .72
FILTERED NITRIFIED LOG Y = 0.07X + 1.65
r = 0.40
FILTERED SECONDARY
FILTERED NITRIFIED
TOTAL COLIFORM (COUNT/100 ML)
ABSORBED OZONE, mg/l

Figure 13. Total coliform density versus absorbed ozone concentration for filtered nitrified and filtered secondary effluents, using oxygen carrier gas.

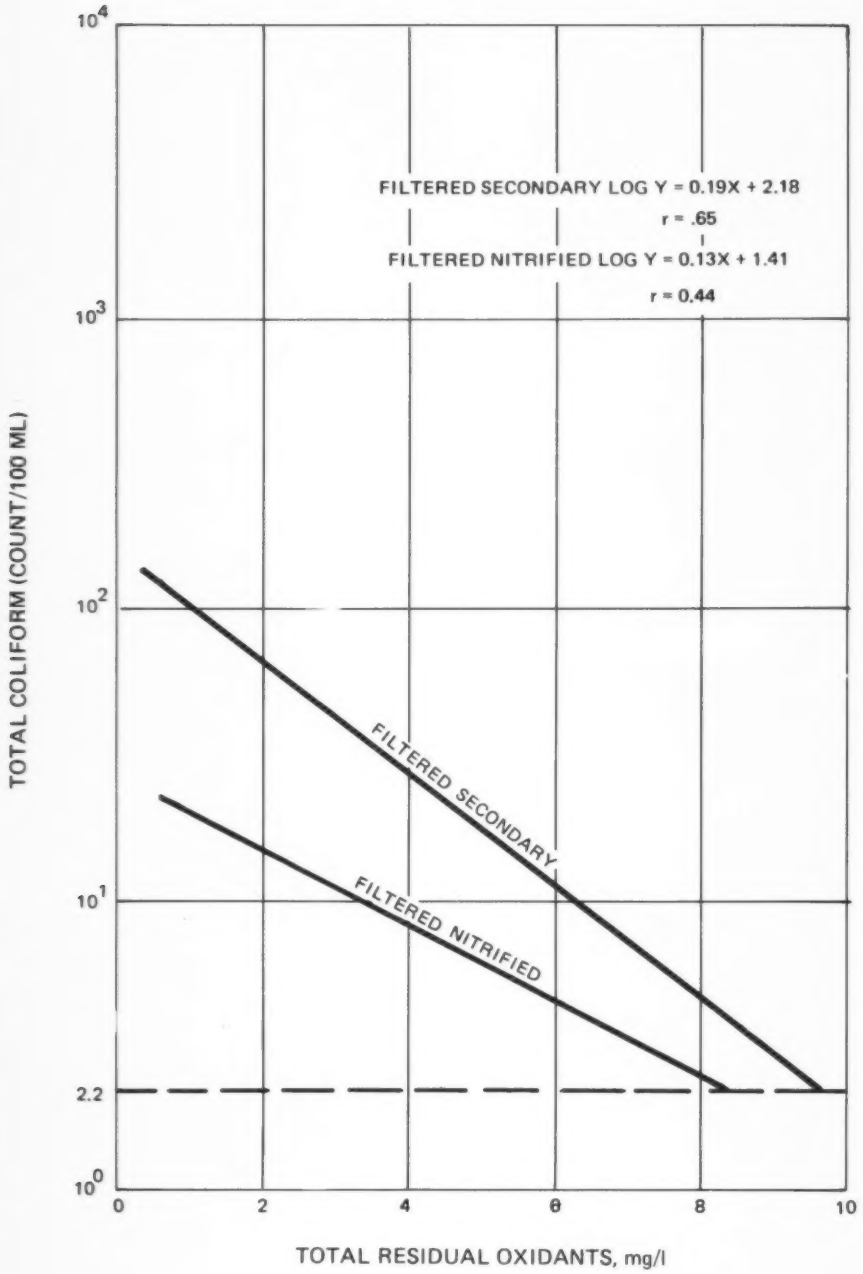

Figure 14. Total coliform density versus total residual oxidants for filtered nitrified and filtered secondary effluents, using oxygen carrier gas.

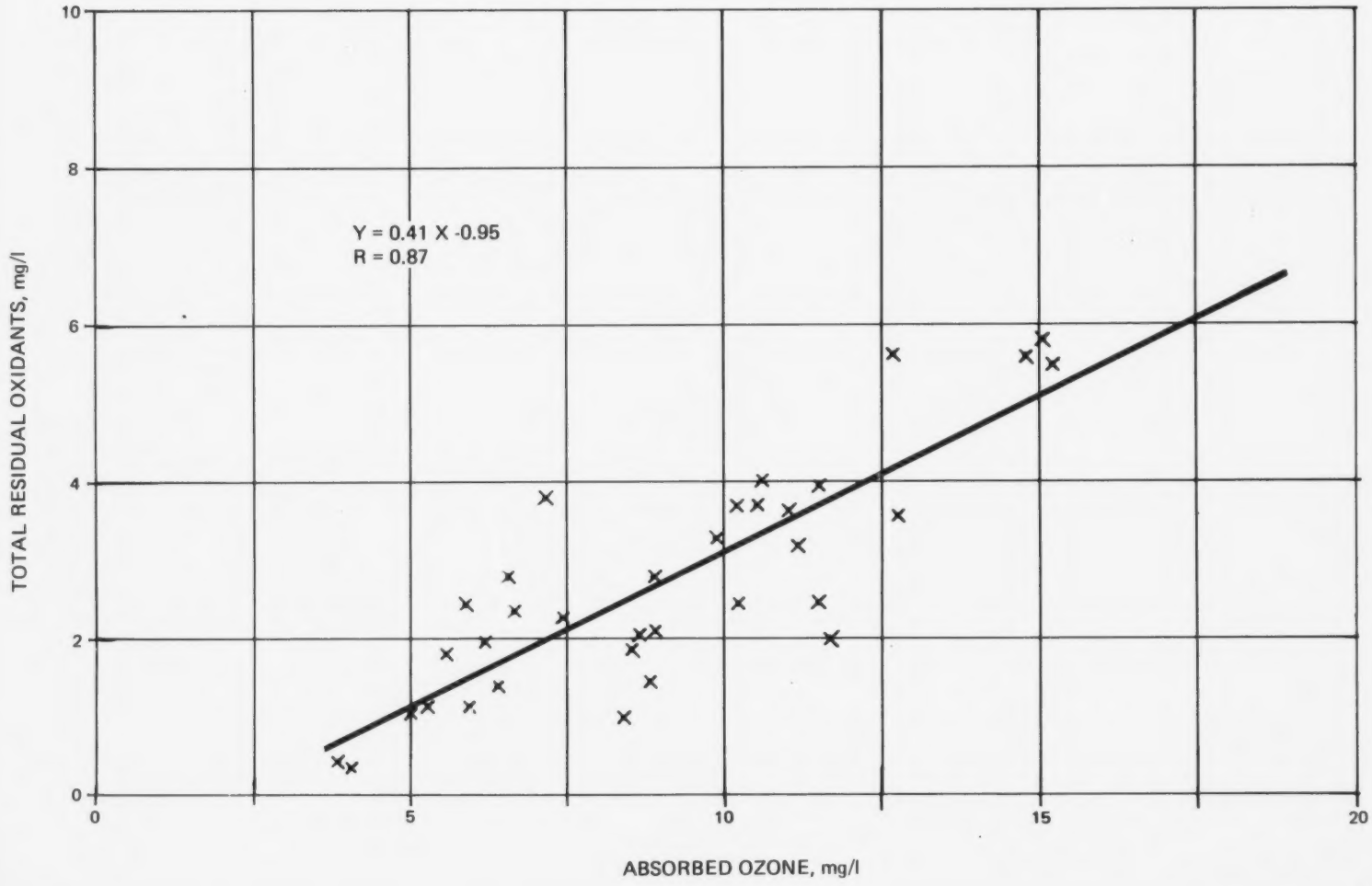

Figure 15. Total residual oxidants versus absorbed ozone concentration for filtered nitrified effluent, using oxygen carrier gas.

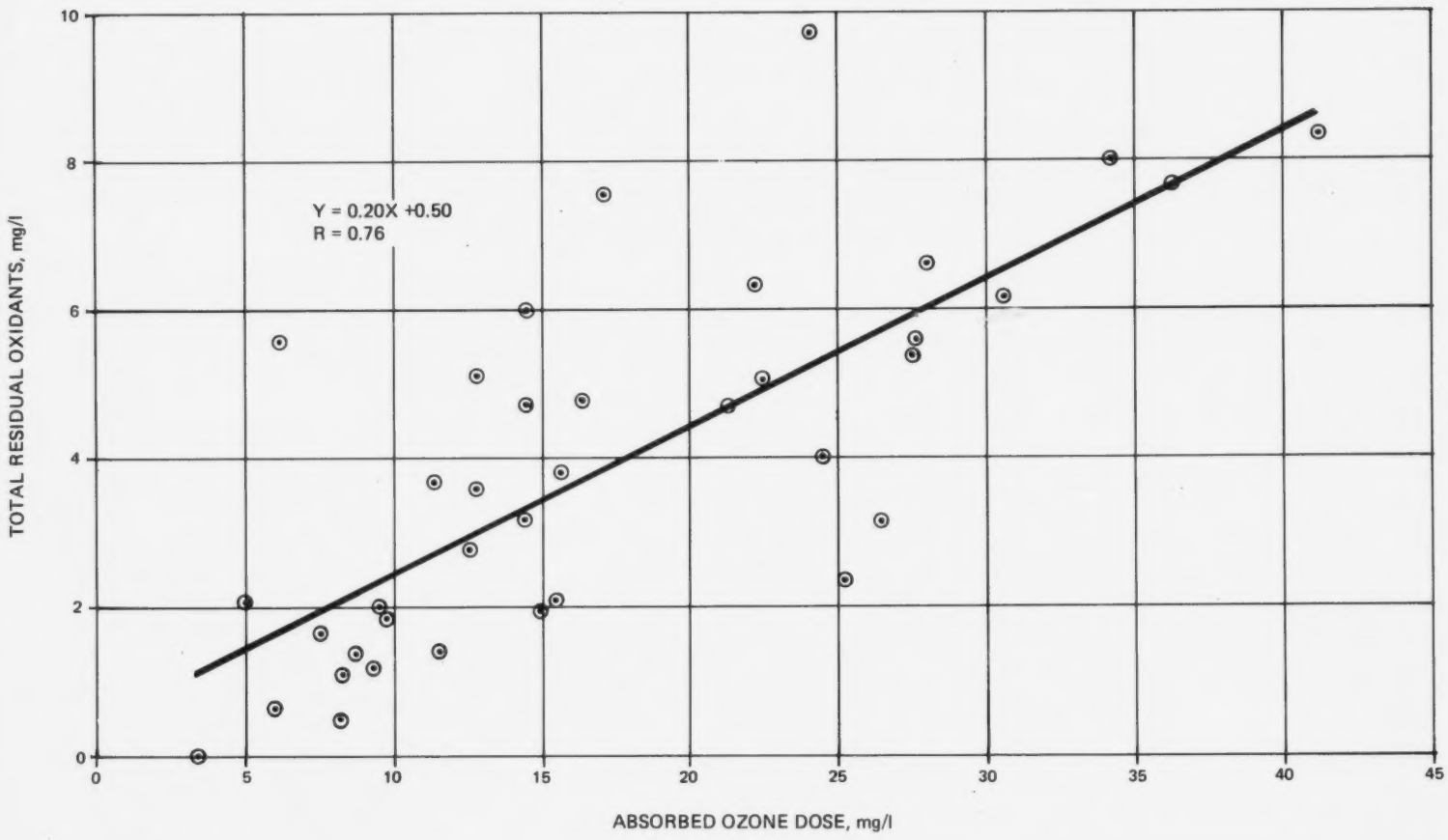

Figure 16. Total residual oxidants versus absorbed ozone concentration for filtered secondary effluent, using oxygen carrier gas.

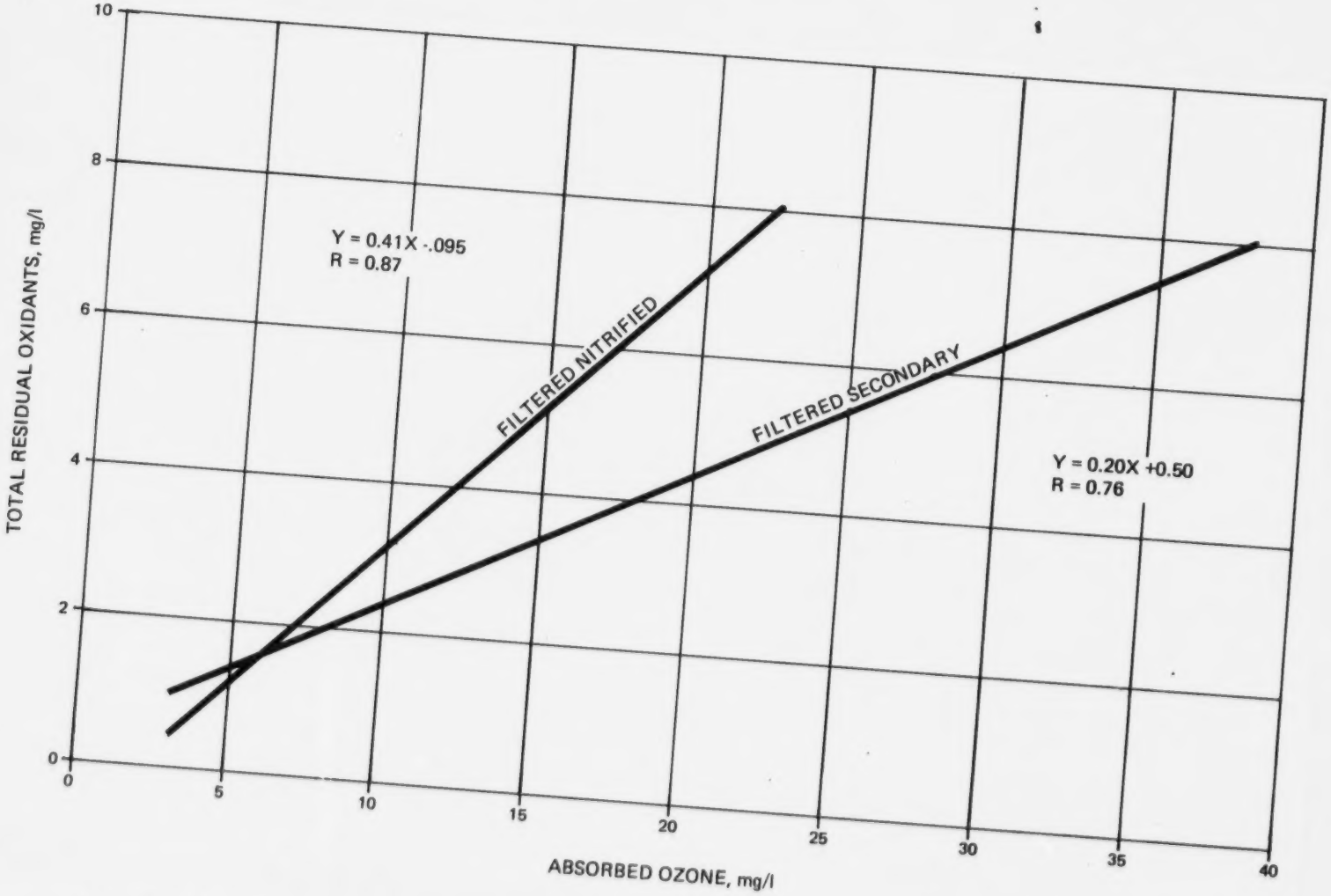

Figure 17. Total residual oxidants versus absorbed ozone concentration for filtered nitrified and filtered secondary effluents, using oxygen carrier gas.

effluent compared to the secondary effluent even though the ozone transfer efficiency was lower in the nitrified effluent, thus achieving the required residual concentrations at lower absorbed ozone concentrations. The DO levels increased to 30 to 45 mg/l in the ozonated effluents. Effluent DO levels of 45 mg/l were reduced to 25 mg/l following vigorous stirring with a magnetic stirrer for approximately 30 minutes.

ENGINEERING AND ECONOMIC EVALUATIONS

Absorbed ozone and total residual oxidant requirements were established for disinfection of Marlborough Easterly filtered nitrified and secondary effluents to 70 and 2.2 total coliforms per 100 ml, as previously described. These requirements were shown to be dependent on water quality but independent of ozone carrier gas source (oxygen versus air). Since water quality influences both the ozone dose requirements and the transfer efficiency, the gas-liquid contacting system capabilities must be defined. The contacting system must be optimized to obtain the minimum ozone requirements for the desired level of disinfection. The contacting system cannot be optimized independently of the ozone generating equipment, because transfer efficiency in the contactor and power requirements for ozone generation are both related to ozone concentration in the carrier gas and the carrier gas flow rate. This section presents the results from the evaluation of the ozone generating and contacting equipment at Marlborough, Massachusetts.

Contactor Mapping

Knowing the absorbed ozone requirements to achieve the desired levels of disinfection, the gas-liquid contacting system was evaluated (mapped) to define the optimized operating conditions by monitoring the percent ozone transferred into the wastewater versus the carrier gas ozone concentration at constant applied doses. The contacting system was mapped in serial countercurrent operation for both filtered nitrified and secondary effluents during operation with both air and oxygen carrier gas.

Air Operation

Results of the contactor mapping evaluations with filtered nitrified effluent during air carrier gas operation are presented graphically in Figures 18, 19 and 20 for the minimum (1.0 l/s), average (2.5 l/s) and maximum (4.0 l/s) effluent flow rates investigated, respectively. Similar results are presented in Figures 21, 22 and 23 for filtered secondary effluent during air carrier gas operation for minimum, average and maximum effluent flow rates, respectively. The results presented in the above mentioned figures were obtained during periods of contactor mapping and supplemented with results from data obtained over the full course of the experimental study.

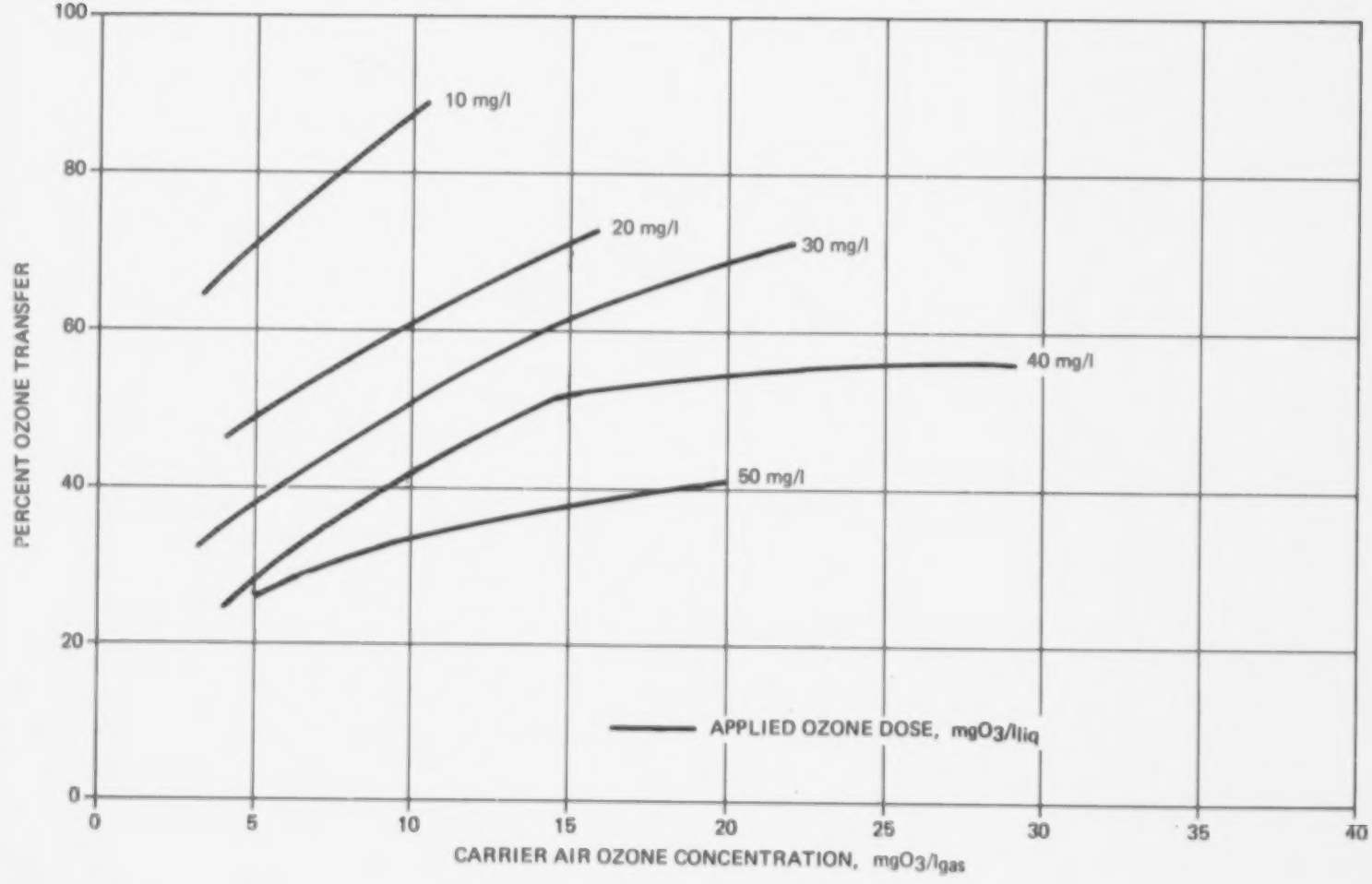

Figure 18. Ozone transfer efficiency at various applied doses for filtered nitrified effluent at minimum effluent flow rate (1.0 l/s), using air carrier gas.

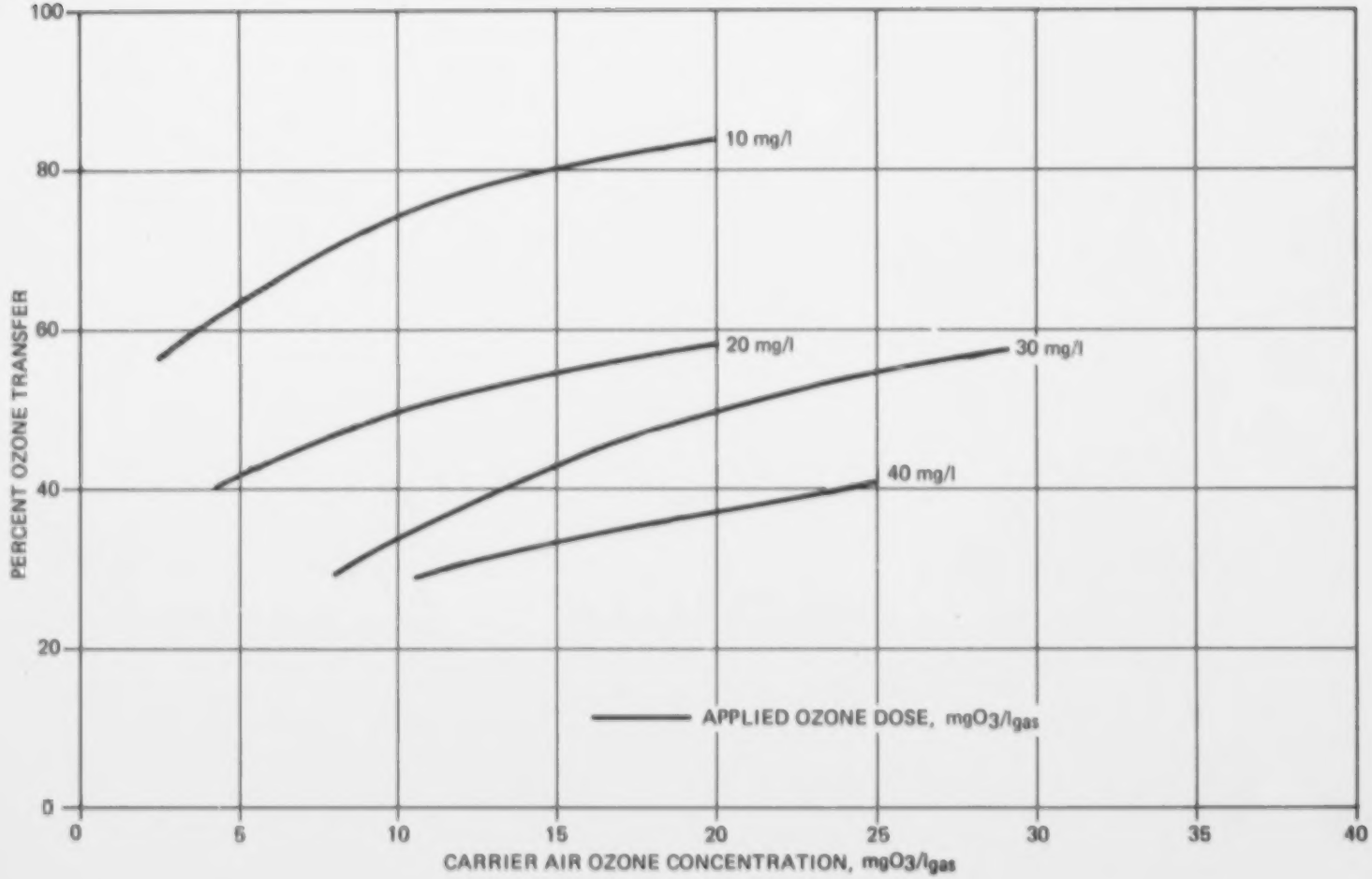

Figure 19. Ozone transfer efficiency at various applied doses for filtered nitrified effluent at average effluent flow rate (2.5 l/s), using air carrier gas.

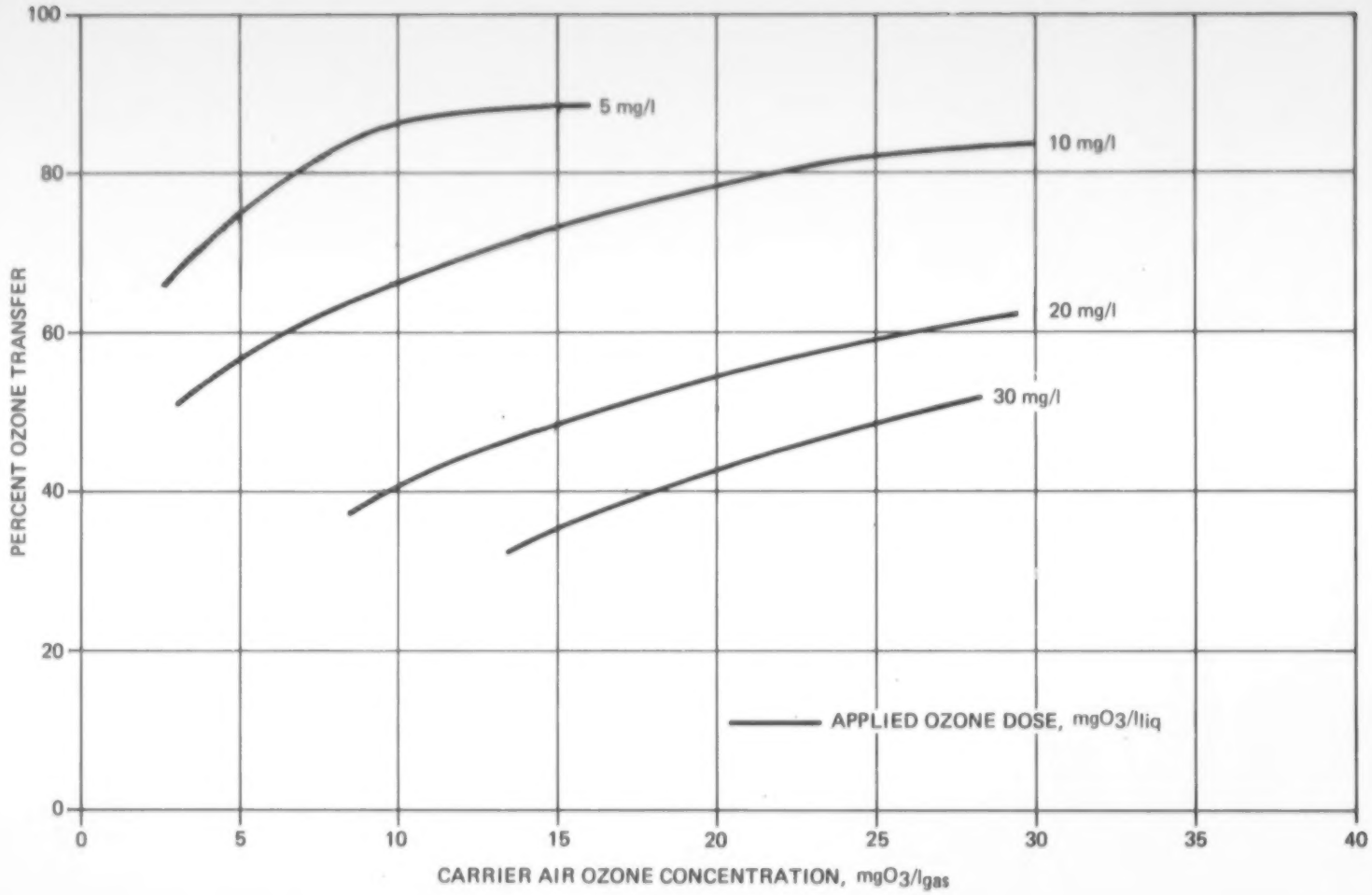

Figure 20. Ozone transfer efficiency at various applied doses for filtered nitrified effluent at maximum effluent flow rate (4.0 l/s), using air carrier gas.

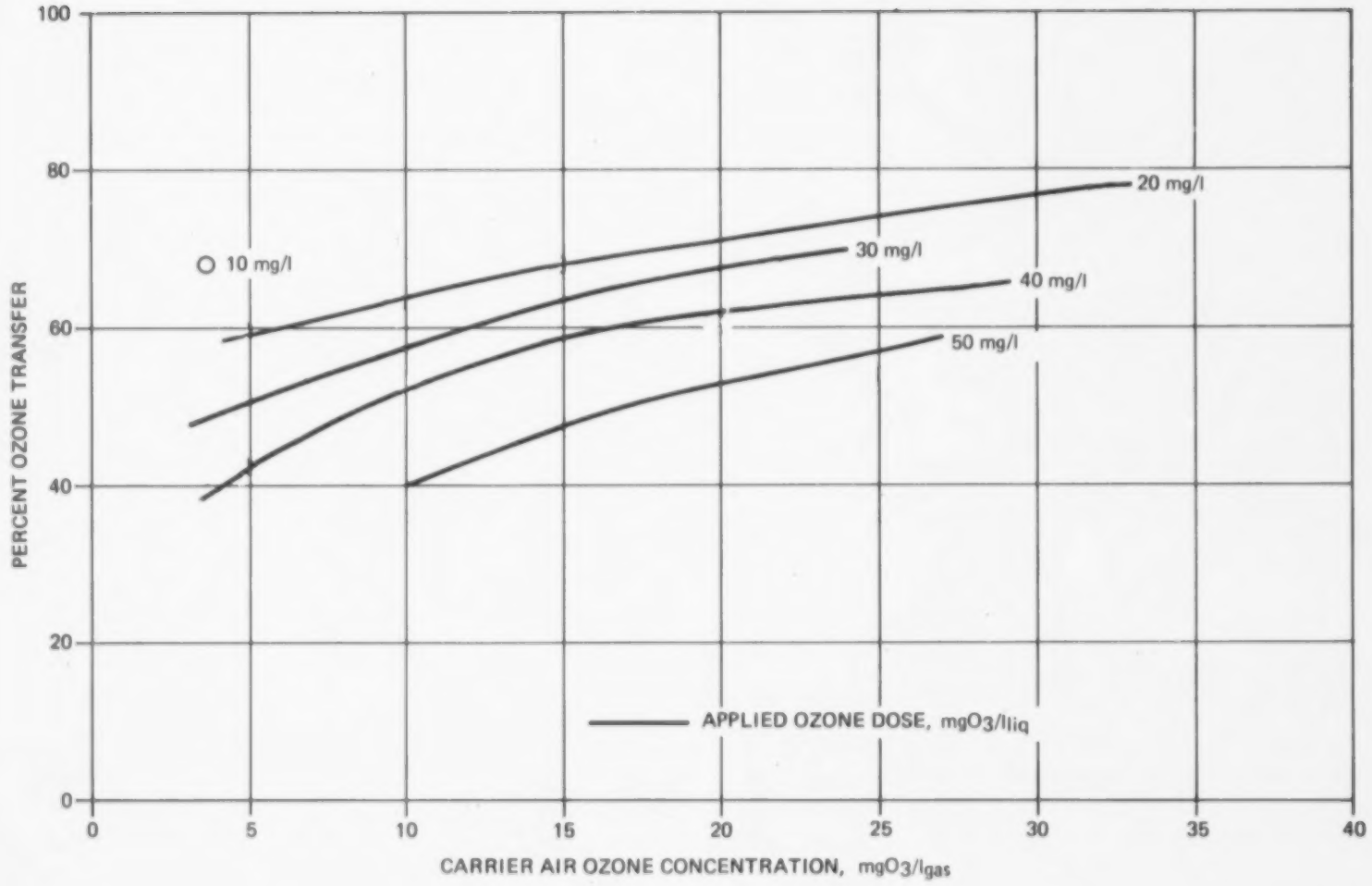

Figure 21. Ozone transfer efficiency at various applied doses for filtered secondary effluent at minimum effluent flow rate (1.0 l/s), using air carrier gas.

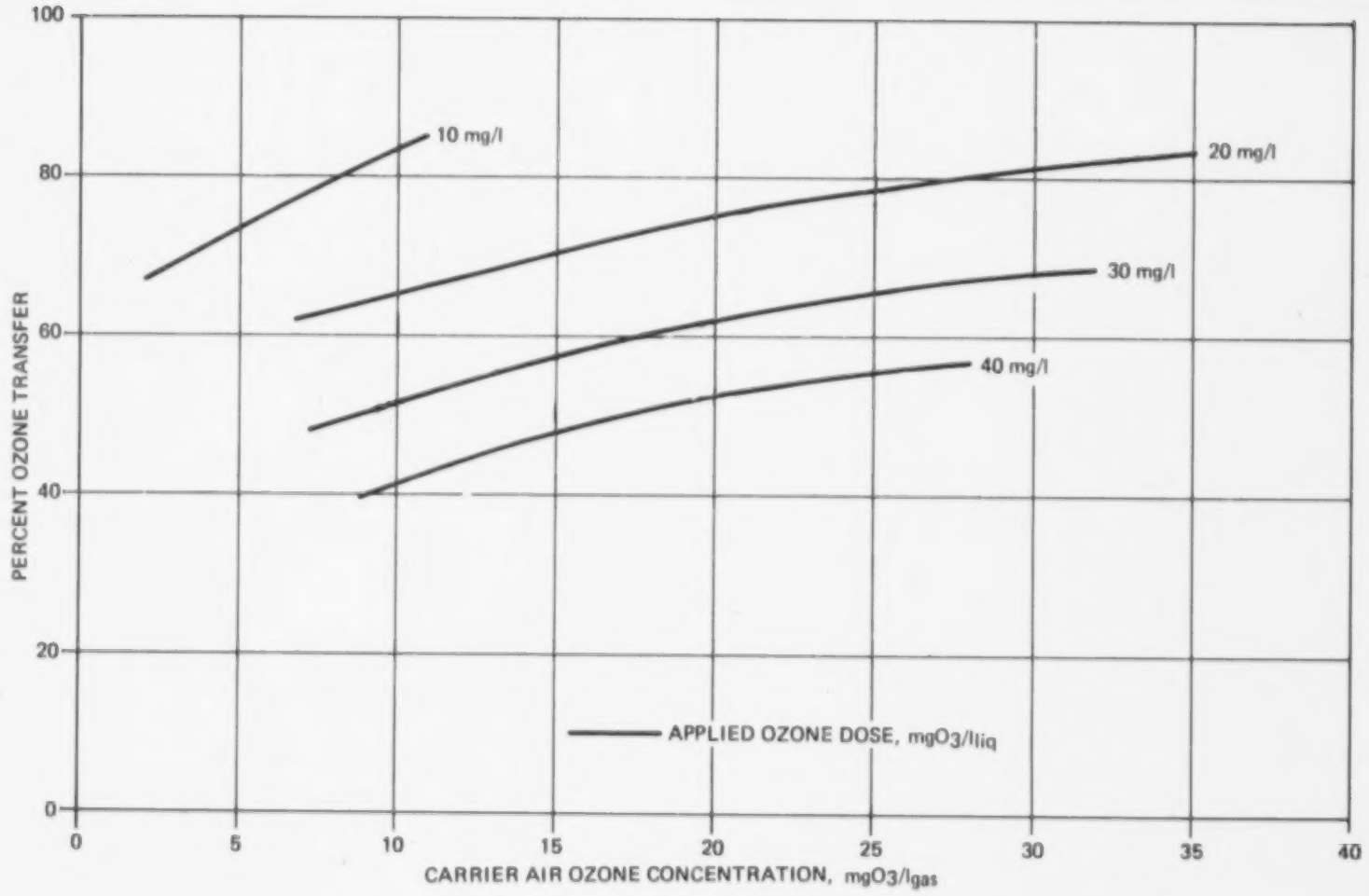

Figure 22. Ozone transfer efficiency at various applied doses for filtered secondary effluent at average effluent flow rate (2.5 l/s), using air carrier gas.

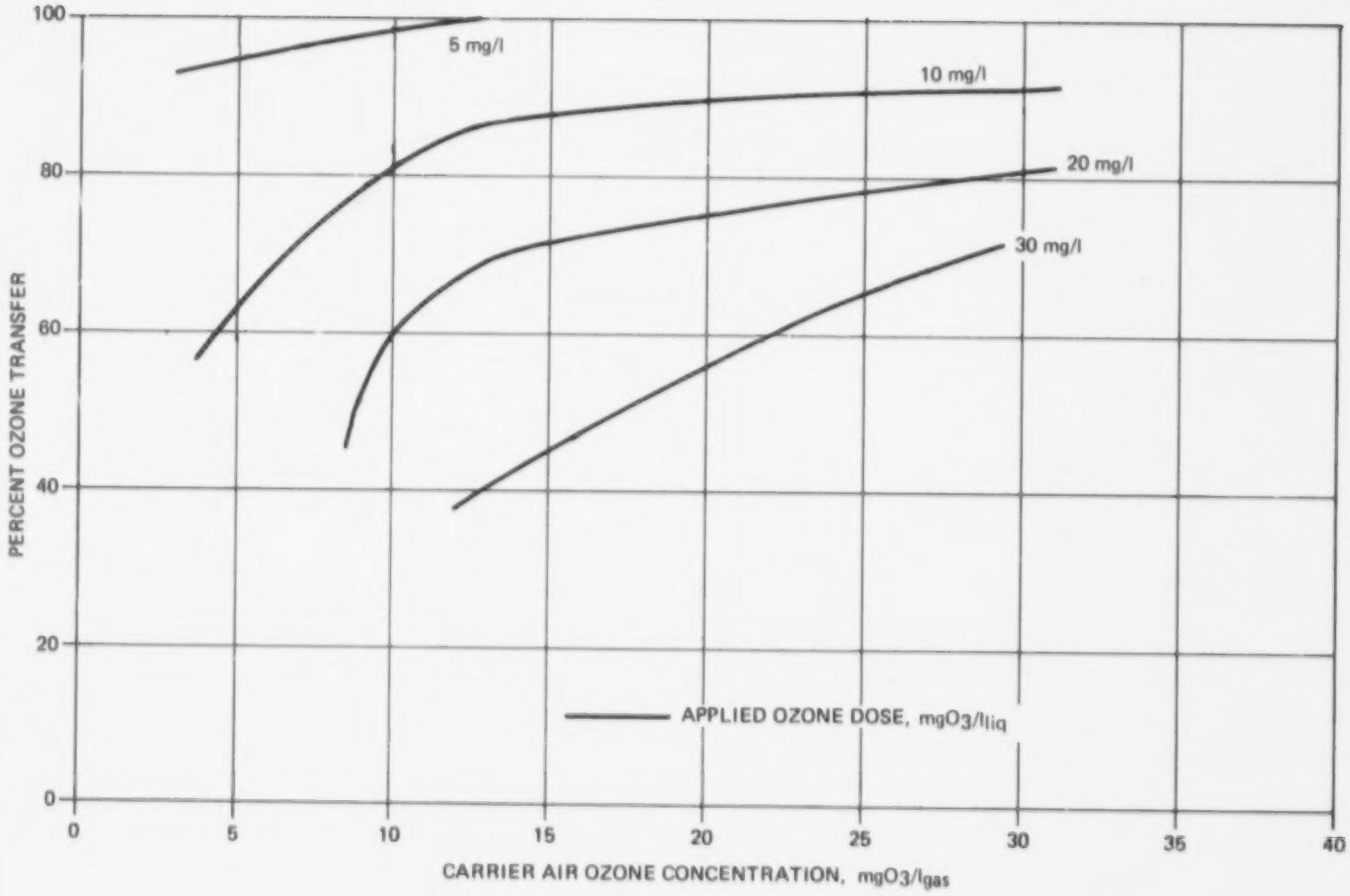

Figure 23. Ozone transfer efficiency at various applied doses for filtered secondary effluent at maximum effluent flow rate (4.0 l/s), using air carrier gas.

Several important observations can be made from Figures 18 through 23, as indicated in Table 13. When the applied dose and subsequently the gas to liquid ratios were increased at a constant carrier gas concentration, the percent ozone transferred into the wastewaters decreased, but the absorbed ozone or quantity of ozone added to the effluent increased. The results in Figures 18 through 23 also show that the percent ozone transferred at any given applied dose increased with increasing carrier gas concentration and corresponding decreasing gas to liquid ratio. At constant operating conditions of applied dose, carrier gas concentration and gas to liquid ratio, the impact of effluent flow rate on transfer efficiency appeared more pronounced with nitrified effluent (Table 13). At the lower hydraulic reaction times, the percent ozone transferred into the poorer quality secondary effluent was higher and less variable than the ozone transferred into the better quality nitrified effluent. As the contactor hydraulic reaction time increased from the minimum of 2.6 minutes to the maximum of 10.6 minutes, the difference in percent ozone transferred between the two effluents decreased and appeared to approach equality. Even though the transfer efficiency was typically lower in the nitrified effluent, lower absorbed ozone concentrations and thus lower applied doses were required to achieve the same level of disinfection compared to secondary effluent.

Oxygen Operation

Results of the contactor mapping evaluations with filtered nitrified effluent during oxygen carrier gas operation are presented graphically in Figures 24 and 25 for the average and maximum effluent flow rates, respectively. Similar results are presented in Figures 26, 27 and 28 for filtered secondary effluent during oxygen carrier gas operation for minimum, average and maximum effluent flow rates, respectively.

The same trends in percent ozone transfer relative to impacts of applied ozone dose, carrier gas ozone concentration and gas to liquid ratio were observed when compared to operation with air carrier gas. As the applied ozone dose and subsequently the gas to liquid ratios were increased at a constant carrier gas concentration, the percent ozone transfer decreased. The percent ozone transfer at any given applied dose increased with increasing carrier gas ozone concentration and corresponding decreasing gas to liquid ratio.

Contactor performance at a constant carrier gas ozone concentration of 20 mg/l from both air and oxygen carrier gas with varying applied doses, gas to liquid ratios and wastewater flow rates has been summarized in Table 14 for both filtered nitrified and secondary effluents. As observed in Table 14, under identical operating conditions of applied ozone dose, carrier gas ozone

TABLE 13. COMPARISON OF OZONE TRANSFER EFFICIENCY FOR FILTERED NITRIFIED AND SECONDARY EFFLUENTS AT CONSTANT CARRIER GAS CONCENTRATION (Y_1 = 20 mg/l) AND VARYING APPLIED DOSES (D) AND GAS TO LIQUID (G/L) RATIOS EMPLOYING AIR CARRIER GAS

Wastewater flow (l/s)	Hydraulic reaction time (min)	D = 10 mg/l G/L = 0.5 Percent transfer		D = 20 mg/l G/L = 1.0 Percent transfer		D = 30 mg/l G/L = 1.5 Percent transfer	
		Nitrified	Secondary	Nitrified	Secondary	Nitrified	Secondary
1.0	10.6	>84	-	>70	72	69	68
2.5	4.3	84	>80	58	76	50	62
4.0	2.6	78	90	54	76	43	56

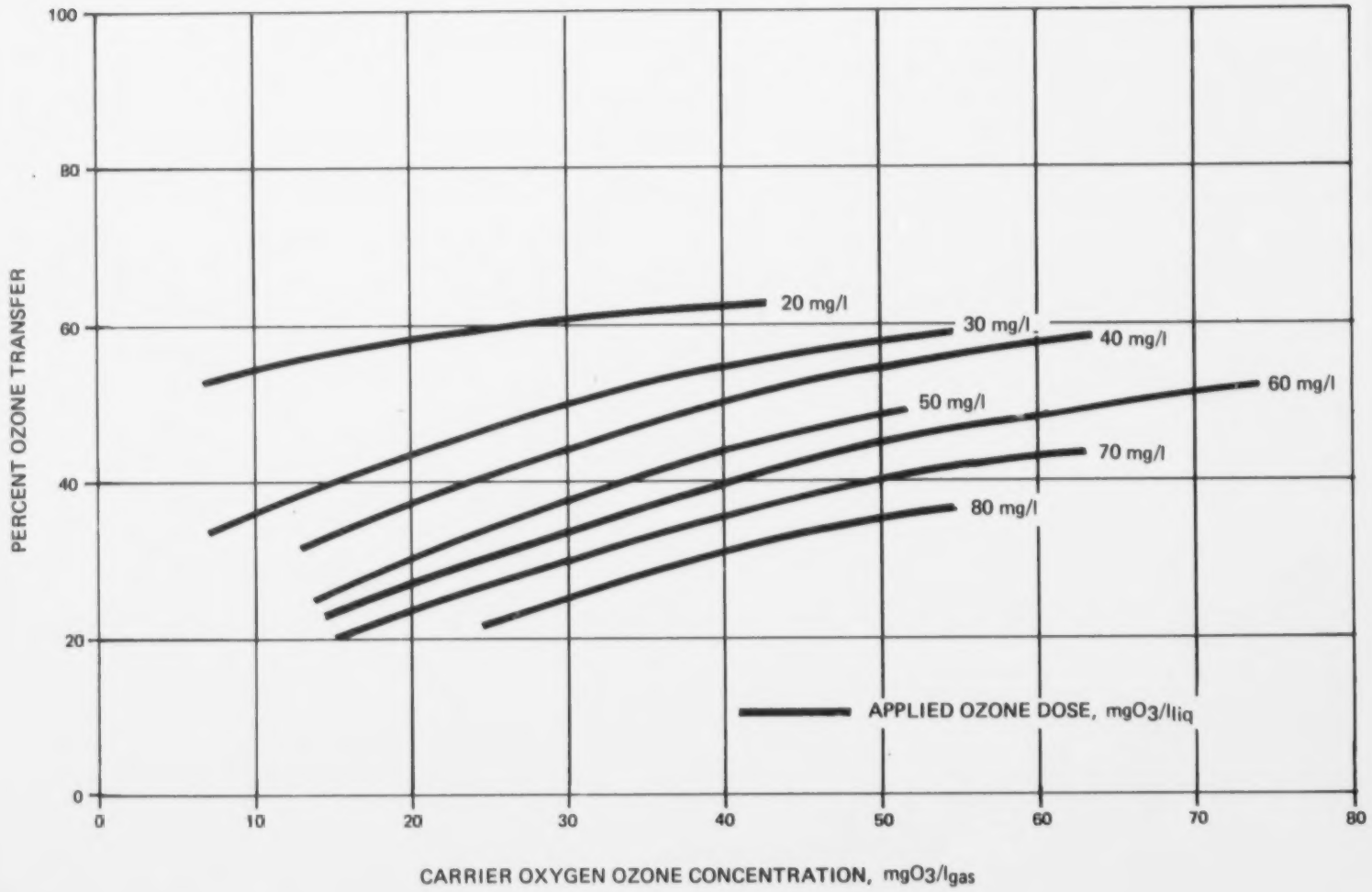

Figure 24. Ozone transfer efficiency at various applied doses for filtered nitrified effluent at average effluent flow rate (2.5 l/s), using oxygen carrier gas.

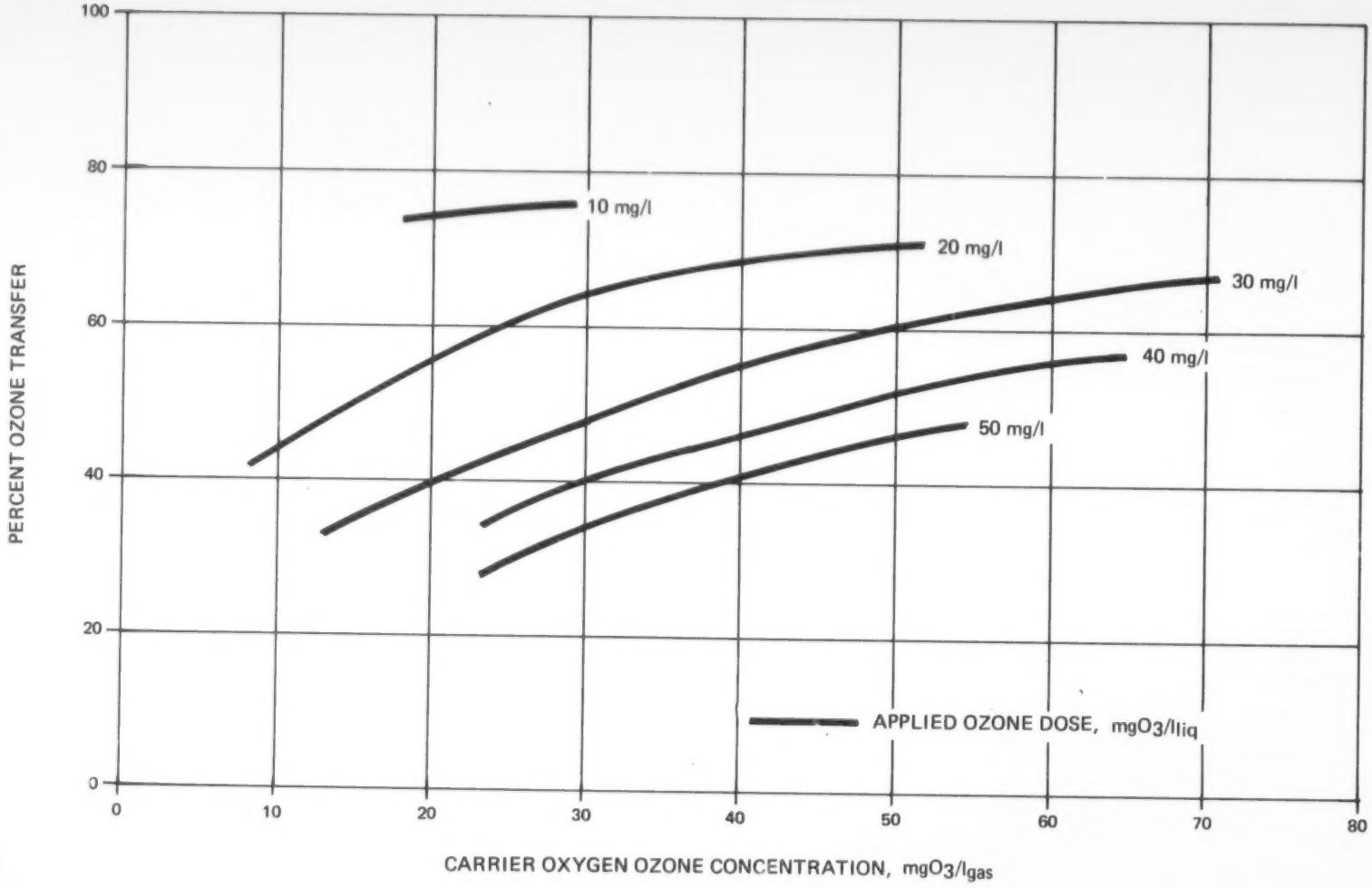

Figure 25. Ozone transfer efficiency at various applied doses for filtered nitrified effluent at maximum effluent flow rate (4.0 l/s), using oxygen carrier gas.

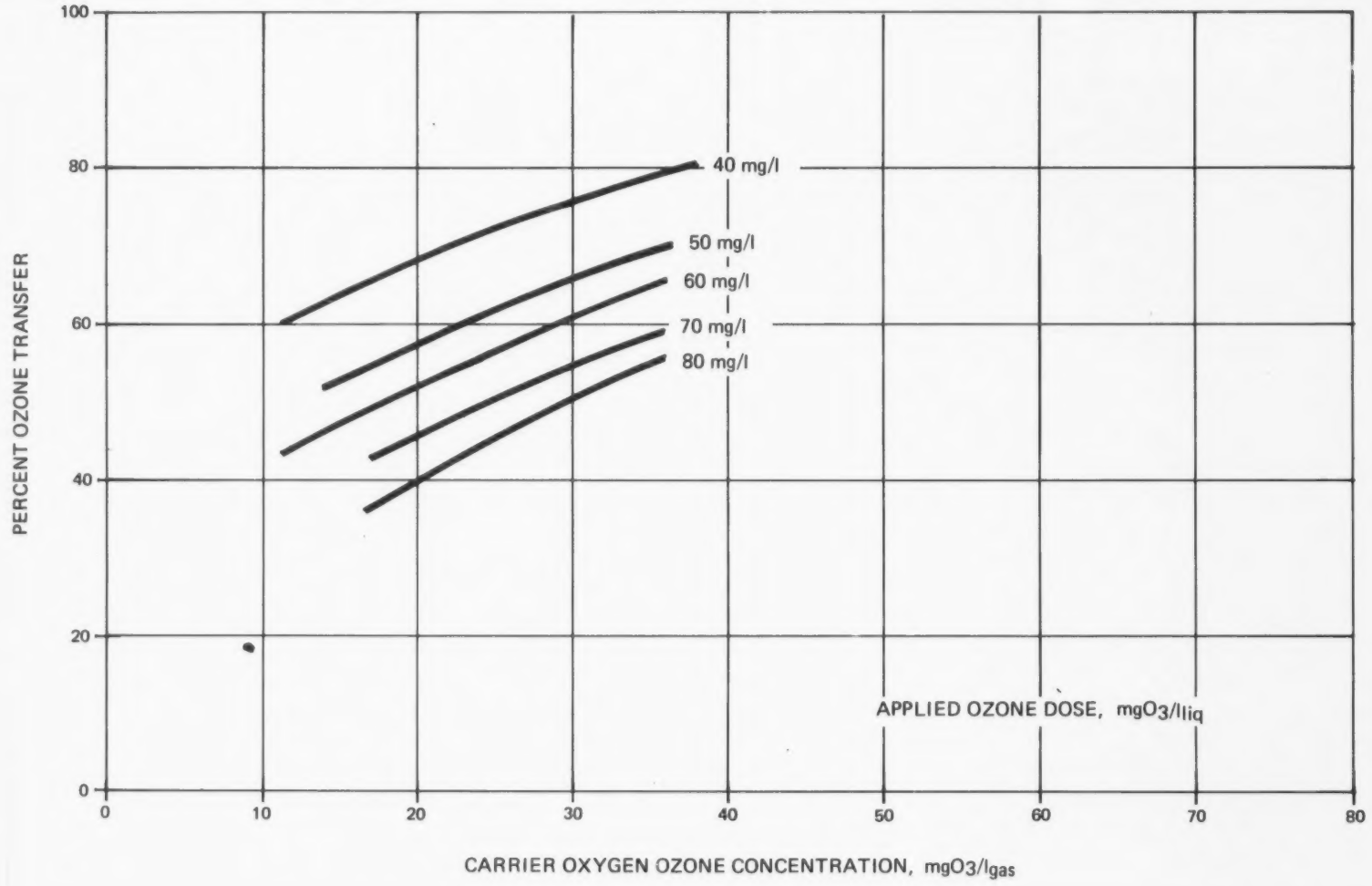

Figure 26. Ozone transfer efficiency at various applied doses for filtered secondary effluent at minimum effluent flow rate (1.0 l/s), using oxygen carrier gas.

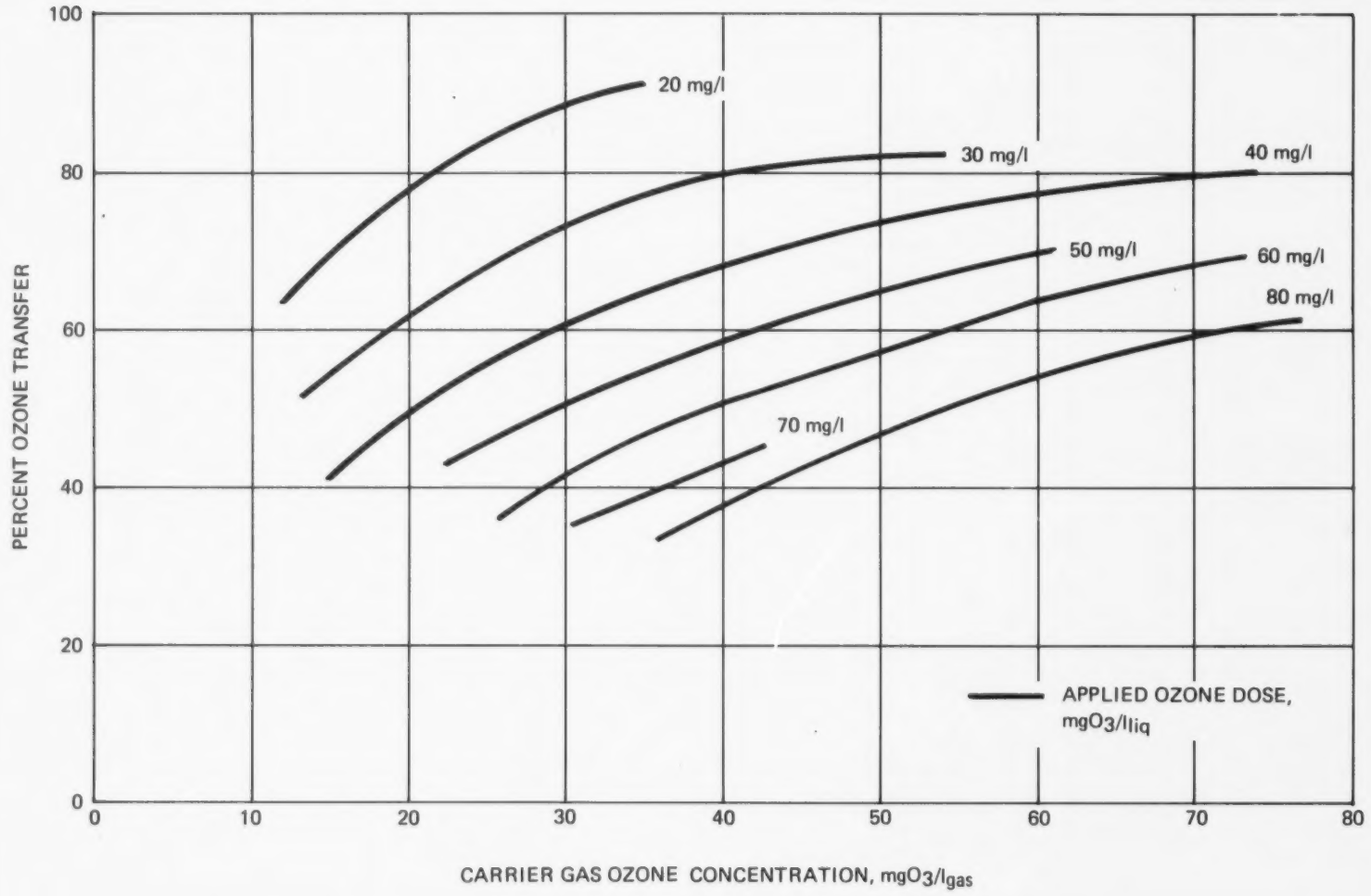

Figure 27. Ozone transfer efficiency at various applied doses for filtered secondary effluent at average effluent flow rate (2.5 l/s), using oxygen carrier gas.

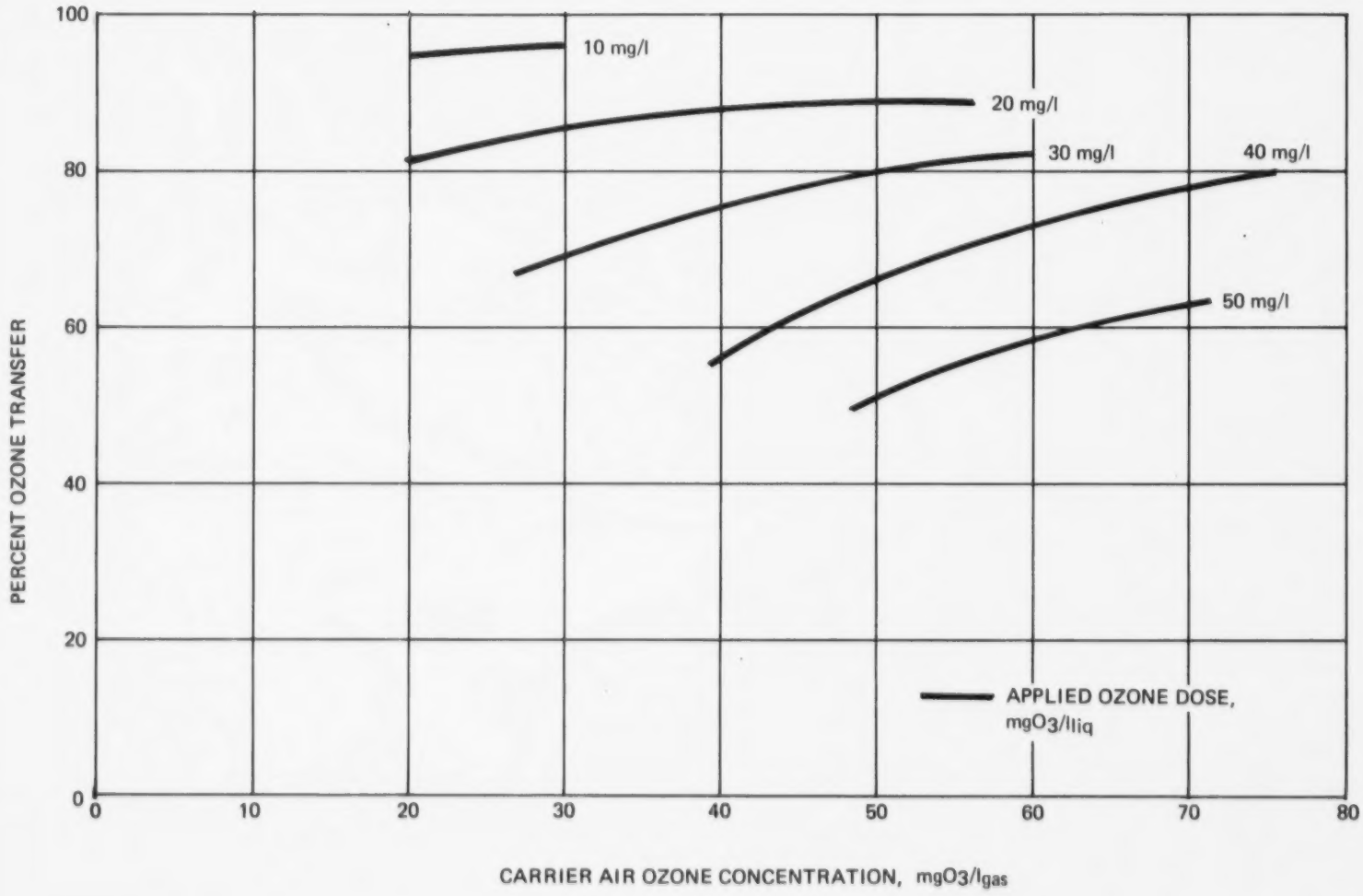

Figure 28. Ozone transfer efficiency at various applied doses for filtered secondary effluent at maximum effluent flow rate (4.0 l/s), using oxygen carrier gas.

TABLE 14. COMPARISON OF OZONE TRANSFER EFFICIENCY FOR FILTERED NITRIFIED AND SECONDARY EFFLUENTS AT CONSTANT CARRIER GAS CONCENTRATION (Y_1 = 20 mg/l) AND VARYING APPLIED DOSES (D) AND GAS TO LIQUID (G/L) RATIOS FOR BOTH AIR AND OXYGEN CARRIER GASES

Wastewater flow (l/s)	Hydraulic reaction time (min)	D = 20 mg/l G/L = 1.0 Percent transfer Air	Oxygen	D = 30 mg/l G/L = 1.5 Percent transfer Air	Oxygen
		NITRIFIED			
1.0	10.6	70	-	69	-
2.5	4.3	58	57	50	45
4.0	2.6	54	55	43	40
		SECONDARY			
1.0	10.6	72	-	68	-
2.5	4.3	76	77	62	62
4.0	2.6	76	82	56	60

concentration, gas to liquid ratio and effluent flow rate, the percent ozone transferred into either effluent (secondary or ntirified) was found to be independent of the type of carrier gas employed. The net impact of ozone generation from oxygen carrier gas was, therefore, higher ozone transfer efficiency due to the higher carrier gas ozone concentrations available. At constant applied ozone doses, contacting efficiency increased with increasing ozone gas concentration and decreasing gas to liquid ratio in all cases.

Generator Mapping

As observed in Figures 18 through 28, several different operating conditions and applied doses with air and oxygen carrier gas could be employed at each flow rate with both effluents to achieve the required absorbed ozone concentrations for the desired levels of disinfection. Therefore, it was necessary to evaluate the ozone generating equipment to define the economics of ozone disinfection. This was accomplished by mapping the ozone generator by monitoring the power consumption versus the ozone produced with both air and oxygen carrier gas.

Air Operation

The ozone carrier gas concentration produced from air over the full range of operating gas flow rates, as determined from the March 1979 mapping, is shown in Figure 29 as a function of the power applied (ozone generator only). The ozone output is shown in Figure 30 as a function of power consumption for the production of one gram of ozone from air (watt hours per gram, W-h/g).

The generator output, as determined in the September 1979 mapping was approximately 5 percent less than the previous March 1979 mapping. Examination of the 210 ozone generating tubes revealed that eight had blown fuses. This represented a 3 percent reduction in total output. Upon replacement of the glass portion of the shorted tubes, and new fuses, the generator output performance was reestablished at the previous level.

Oxygen Operation

The ozone carrier gas concentration produced from oxygen over the range of operating gas flow rates is shown in Figure 31 as a function of the power applied (ozone generator only). Comparison of generator performance with oxygen carrier gas (Figure 31) to performance with air carrier gas (Figure 29) indicates that twice the ozone gas concentration was produced during operation with oxygen at the same operating conditions. Therefore, twice the ozone output per unit power consumption by the generator was available during operation with oxygen carrier gas, as observed in Figure 32.

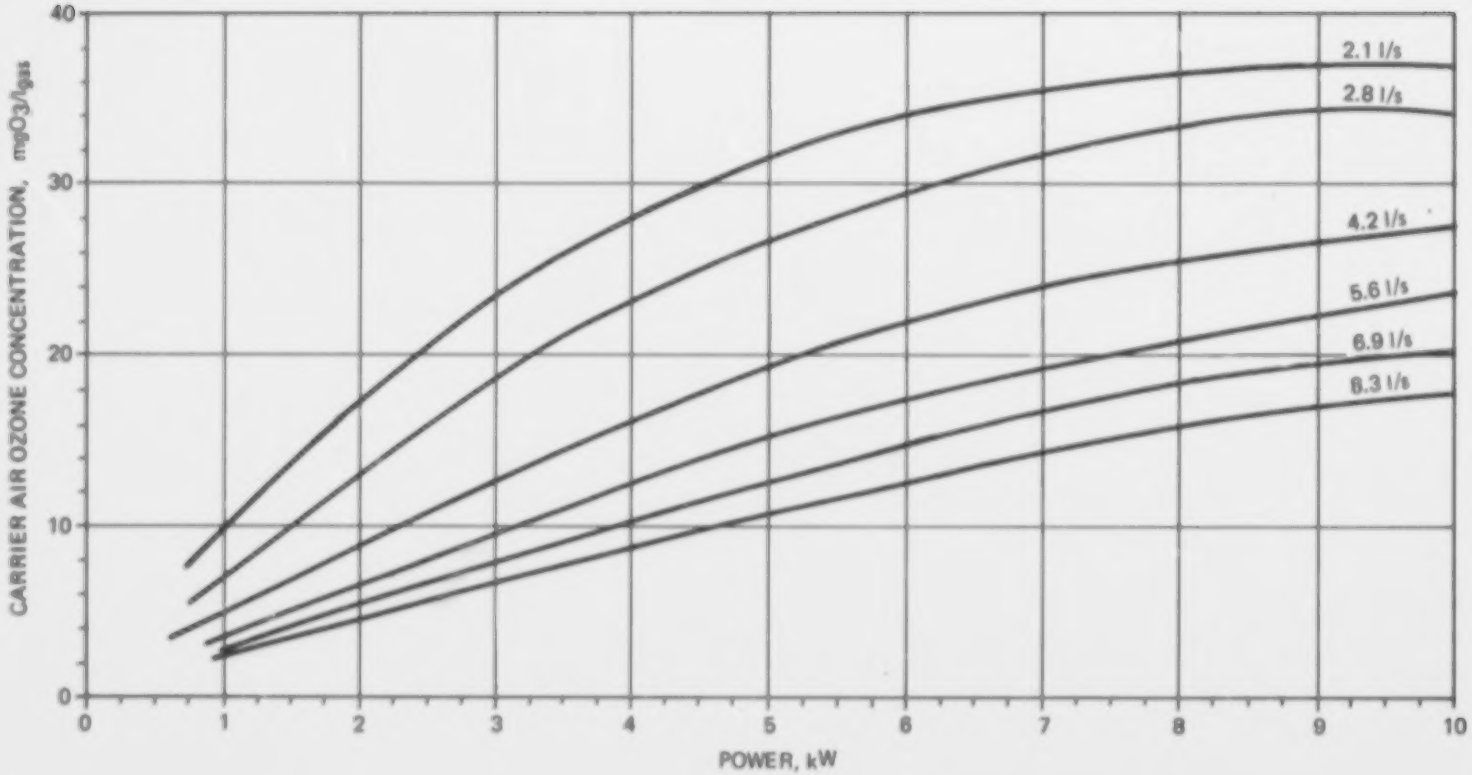

Figure 29. Generator performance - ozone concentration versus power at dew point between -45 to -50 Deg. C. for various gas flow rates using air carrier gas.

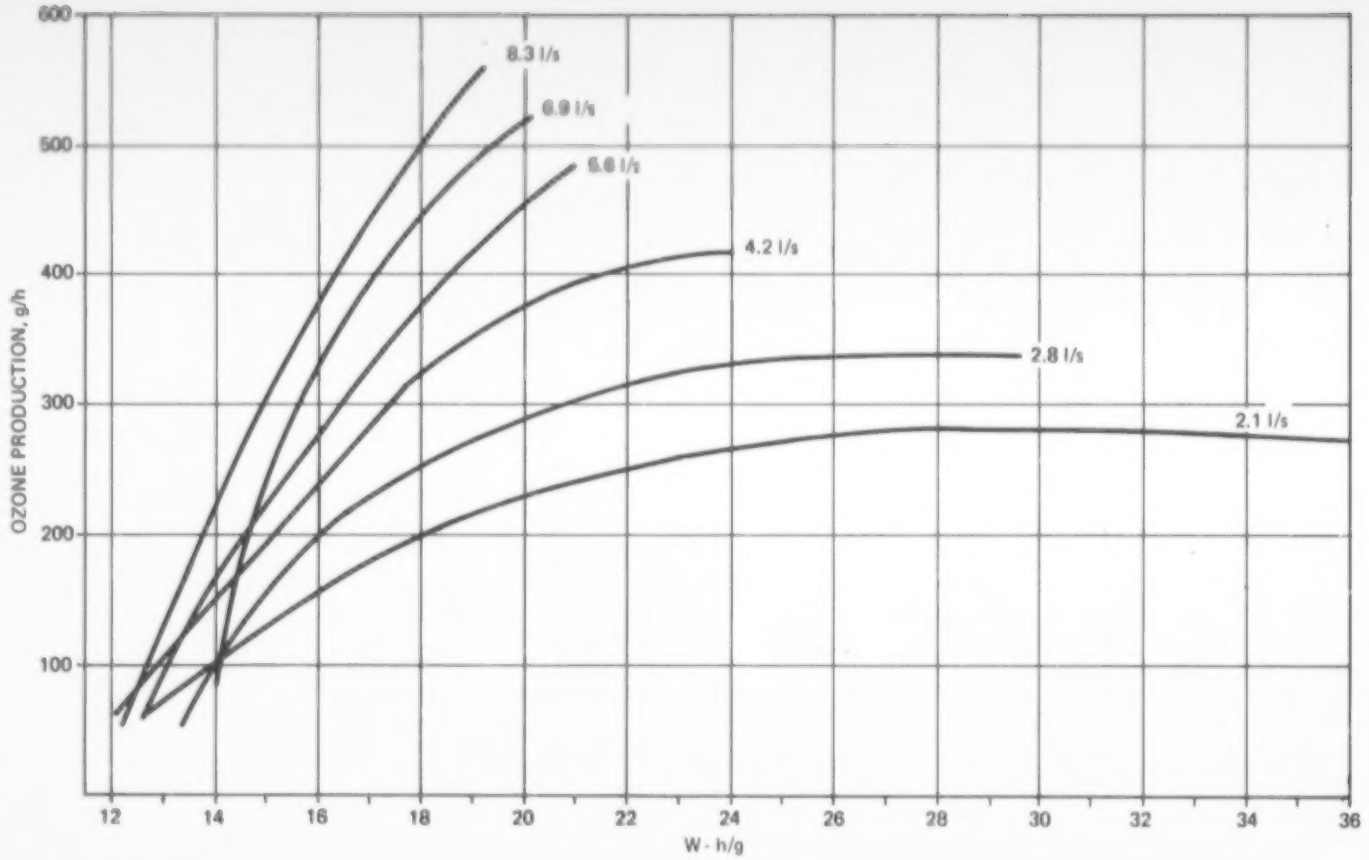

Figure 30. Generator performance - Ozone production versus power consumption at various gas flow rates, using air carrier gas.

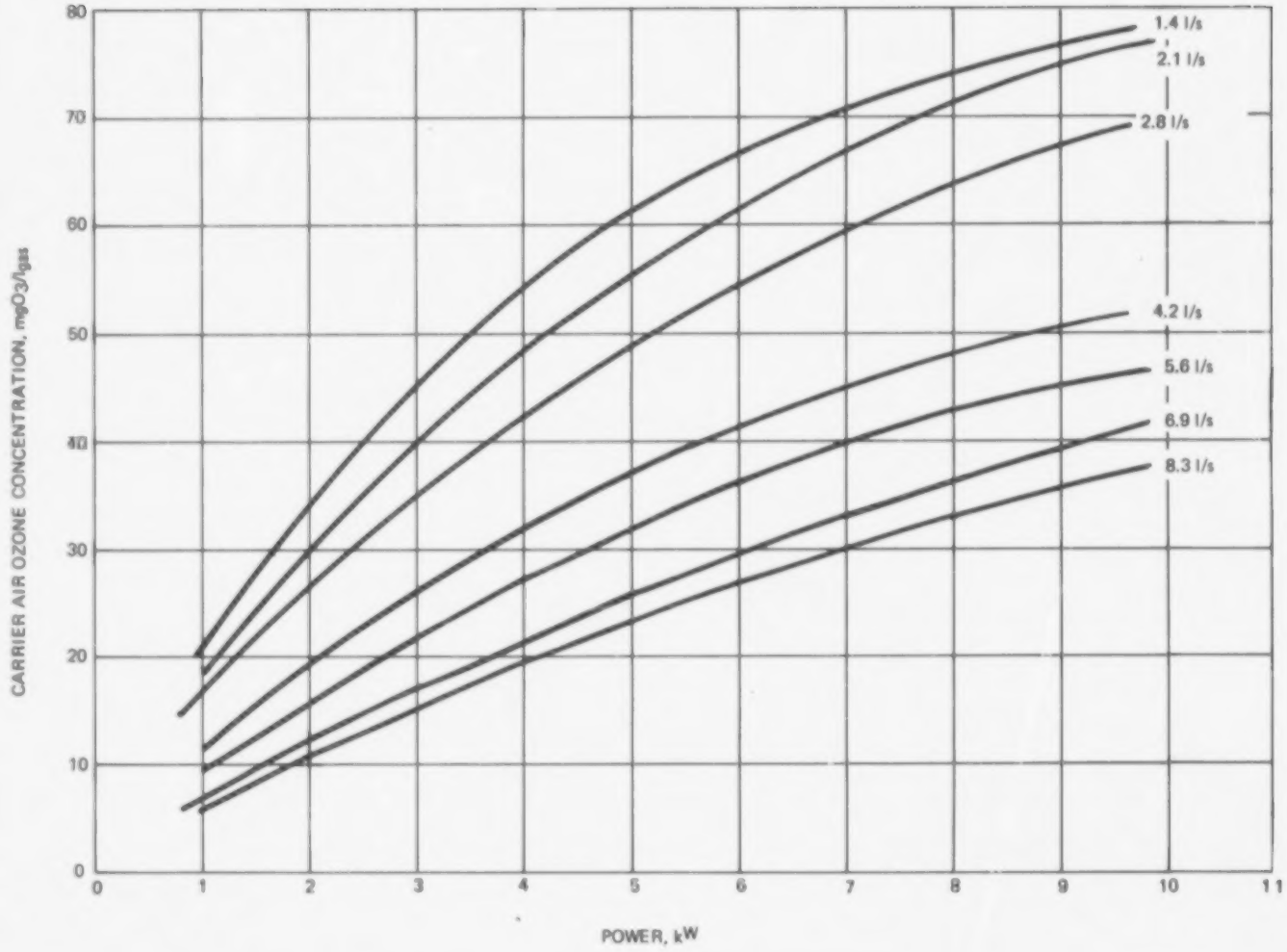

Figure 31. Generator performance - Ozone concentration versus power for various gas flow rates, using oxygen carrier gas.

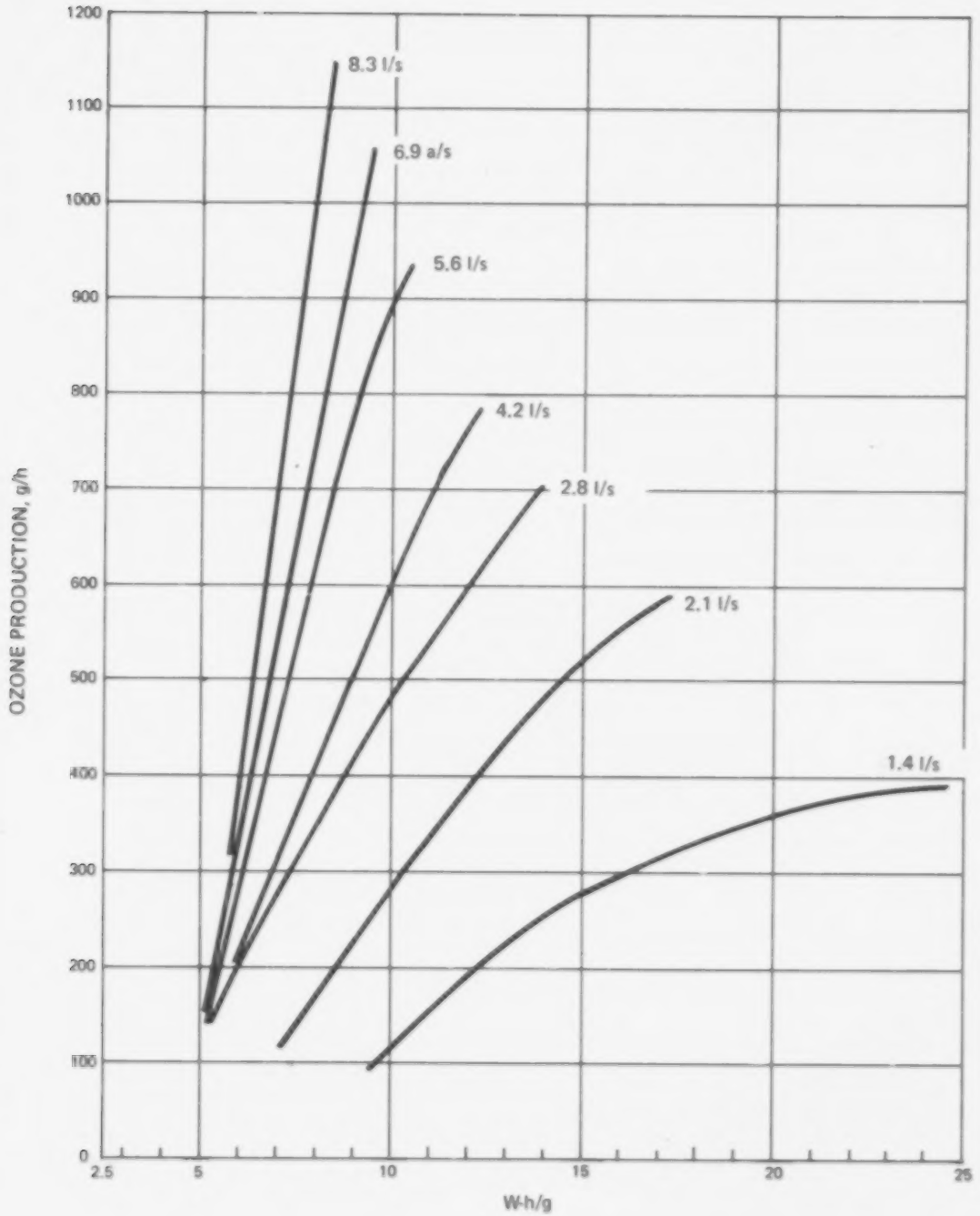

Figure 32. Generator performance - Ozone production versus power consumption at various gas flow rates using oxygen carrier gas.

Generator-Contactor Evaluation - Air Operation

In combining the contactor evaluation during air carrier gas operation (Figures 18 through 23) with the generator evaluation (Figures 29 and 30) the ozone generating-contacting system can be optimized for the various levels of disinfection required, as presented in Tables 15, 16 and 17. The information in Table 15 indicates that disinfection of filtered nitrified effluent to 70 total coliforms/100 ml at an absorbed ozone requirement of 5 to 8 mg/l can be accomplished at applied doses of 10, 20 and 30 mg/l. However, the transfer efficiency is higher (approximately 85 percent), the generator output is lower and the power requirements are optimized at 13 to 16 W-h/g (5.9 to 7.3 kW-h/lb) of ozone produced at 10 mg/l applied dose and 0.5 to 2.3 kW draw, indicating this operating condition to be optimized for both ozone contacting and ozone generation.

The information presented in Table 16 indicates that disinfection of filtered nitrified effluent to 2.2 total coliforms/100 ml at an absorbed ozone requirement of 15 to 20 mg/l can only be accomplished at all effluent flow rates at an applied dose of 30 mg/l. Applied ozone doses of 40 and 50 mg/l at the higher flow rates were beyond the generator capabilities with air operation. Disinfection at an applied dose of 30 mg/l is within the optimum generator operating range at the minimum and average effluent flow rates with power requirements of 13 to 19 W-h/g (5.9 to 8.6 kW-h/lb) of ozone produced and 1.5 to 5.1 kW draw. At the maximum wastewater flow rate the ozone production required is pushing the generating system out of the optimum operating range at 25 W-h/g (11.3 kW-h/lb) and 10.8 kW draw.

The information presented in Table 17 indicates that disinfection of filtered secondary effluent to 70 total coliforms/100 ml at an absorbed ozone requirement of 15 to 20 mg/l can be accomplished with applied doses of 20 and 30 mg/l. At an applied dose of 40 mg/l, the required ozone output is beyond the capability of the generator, operating with air carrier gas, at the maximum flow rate. However, at the 20 mg/l applied dose, the transfer efficiency is higher (approximately 80 percent), the generator output is lower and the power requirements are within the optimum range at 18 W-h/g (8.2 kW-h/lb) of ozone produced and 3.1 to 5.4 kW draw.

The total power draw in kW of the complete ozone disinfection system with air carrier gas was monitored over each of the two five day continuous operating periods. The thermal destruct unit required a constant 4.2 kW power draw. The two ozone contactors averaged 2.6 kW draw each, however, it must be remembered that each contactor was oversized for the series operation mode to allow the total pilot plant flow to be disinfected in each contactor. This design was developed for the pilot plant to provide the operational flexibility required for evaluation of

TABLE 15. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT EMPLOYING AIR CARRIER GAS
Required Absorbed Ozone = 5-8 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output g/h	Power W-h/g	Requirement kW
			Applied Ozone Dose = 10 mg/l						
18	1.0	7	78	7.8	1.4	1.4	36	13	0.5
19	2.5	20	84	8.4	1.2	0.5	90	14	1.3
20	4.0	22	80	8.0	1.8	0.5	143	16	2.3
			Applied Ozone Dose = 20 mg/l						
18	1.0	4	48	9.6	5.0	5.0	72	13	0.9
19	2.5	8	48	9.6	6.3	2.5	180	14	2.5
20	4.0	16	48	9.6	5.0	1.3	288	16	4.6
			Applied Ozone Dose = 30 mg/l						
18	1.0	4	34	10.2	7.5	7.5	108	13	1.4
19	2.5	9	34	10.2	8.3	3.3	270	15	4.1
20	4.0	16	35	10.5	7.5	1.9	432	17	7.3

TABLE 16. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 2.2 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT EMPLOYING AIR CARRIER GAS
(Required Absorbed Ozone Dose = 15-20 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output g/h	Power W-h/g	Requirement kW
				Applied Ozone Dose = 30 mg/l					
18	1.0	20	68	20.4	1.5	1.5	108	14	1.5
19	2.0	26	55	16.5	2.9	1.2	270	19	5.1
20	4.0	30	50	15.0	4.0	1.0	432	25	10.8
				Applied Ozone Dose = 40 mg/l					
18	1.0	20	54	21.6	2.0	2.0	144	16	2.3
19	2.5	26	42	16.8	3.8	1.5	359	20	7.2
20	4.0	-	-	-	-	-	-	-	-
				Applied Ozone Dose = 50 mg/l					
18	1.0	18	40	20.0	2.8	2.8	180	16	2.9
19	2.5	-	-	-	-	-	-	-	-
20	4.0	-	-	-	-	-	-	-	-

TABLE 17. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED SECONDARY EFFLUENT EMPLOYING AIR CARRIER GAS
(Required Absorbed Ozone = 15-20 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output (g/h)	Power (W-h/g)	Requirement kW
				Applied Ozone Dose = 20 mg/l					
21	1.0	30	78	15.6	0.7	0.7	72	-	-
22	2.5	26	80	16.0	1.9	0.8	180	17	3.1
23	4.0	26	80	16.0	3.1	0.8	286	19	5.4
				Applied Ozone Dose = 30 mg/l					
21	1.0	10	60	18.0	3.0	3.0	108	14	1.5
22	2.5	18	60	18.0	4.2	1.7	270	17	4.6
23	4.0	22	60	18.0	5.4	1.4	431	19	8.2
				Applied Ozone Dose = 40 mg/l					
21	1.0	6	46	18.4	6.7	6.7	144	14	2.0
22	2.5	14	46	18.4	7.1	2.9	360	16	5.8
23	4.0	-	-	-	-	-	-	-	-

high level disinfection. The power draw by the ozone generator and air preparation equipment was variable, while that of the thermal destruct unit and the two contactors was constant.

The average power requirement over the five day period during disinfection of nitrified effluent to less than 2.2 total coliforms per 100 ml for ozone generation was 27 kW-h/kg and 29 kW-h/kg for ozone generation and air preparation. Total power requirements for the entire system including air preparation, ozone generation, contacting and thermal destruct averaged 45 kW-h/kg of ozone produced. This number (45 kWh/kg) is only representative of this pilot plant, since the generator was not optimized for this level of ozone production from carrier air operation and both contactors were oversized to handle the entire effluent flow.

The average power requirement for ozone generation over the five day test period during disinfection of secondary effluent to the geometric mean of 32 total coliforms per 100 ml as previously discussed was 22 kW-h/kg, and 24 kW-h/kg was required for ozone generation and air preparation. Total power requirements for the entire system described above averaged 42 kW-h/kg of ozone produced. Again, this number is only representative of this pilot plant without optimization of ozone generation and with oversized contactors.

The power requirements for ozone generation alone (27 kW-h/kg and 22 kW-h/kg for nitrified and secondary effluents, respectively) were beyond the optimum operating range for ozone production by this generator with air carrier gas (13-19 kW-h/kg) as can be seen by comparison with the generator mapping curves. Lower power requirements for ozone production could be realized with a larger ozone generator or by operating the existing generator with oxygen carrier gas.

Generator-Contactor Evaluation - Oxygen Operation

In combining the contactor evaluation during oxygen carrier gas operation (Figures 24 through 28) with the generator evaluation (Figures 31 and 32) the ozone generating-contacting system can be optimized for the various levels of disinfection required. Several different operating conditions and applied doses could be employed at each effluent flow rate to achieve the required absorbed ozone concentrations. The information presented in Tables 18 and 19 summarizes the different operating conditions and generator power requirements for achieving 70 and 2.2 total coliforms/100 ml with filtered nitrified effluent respectively. The information presented in Tables 20 and 21 summarizes the different operating conditions and generator power requirements for achieving 70 and 2.2 total coliforms/100 ml with filtered secondary effluent respectively.

TABLE 18. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT EMPLOYING OXYGEN CARRIER GAS
(Required Absorbed Ozone = 5-8 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output (g/h)	Power (W-h/g)	Requirement kW
				Applied Ozone Dose = 20 mg/l					
24	2.5	10	55	11.0	5.0	2.0	180	5.5	1.0
25	4.0	10	42	8.4	8.0	2.0	288	5.5	1.6
				Applied Ozone Dose = 30 mg/l					
24	2.5	10	34	10.2	7.5	3.0	270	5.5	1.5
25	4.0	15	34	10.2	8.0	2.0	432	6.0	2.6
				Applied Ozone Dose = 40 mg/l					
24	2.5	12	28	11.2	8.3	3.3	360	6.0	2.2
25	4.0	15	27	10.8	10.7	2.7	576	6.0	3.5

TABLE 19. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 2.2 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT EMPLOYING OXYGEN CARRIER GAS
(Required Absorbed Ozone = 15-20 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output (g/h)	Power (W-h/g)	Requirement kW
			Applied Ozone Dose = 30 mg/l						
24	2.5	30	50	15.0	2.5	1.0	270	7.5	2.2
25	4.0	30	50	15.0	4.0	1.0	432	8.5	3.7
			Applied Ozone Dose = 40 mg/l						
24	2.5	24	40	16.0	4.2	1.7	360	7.5	2.7
25	4.0	30	40	16.0	5.3	1.3	576	7.5	4.3
			Applied Ozone Dose = 50 mg/l						
24	2.5	25	34	17.0	5.0	2.0	450	7.5	3.4
25	4.0	30	33	16.5	6.7	1.7	720	8.0	5.7

TABLE 20. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED SECONDARY EFFLUENT EMPLOYING OXYGEN CARRIER GAS
(Required Absorbed Ozone = 15-20 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output (g/h)	Power (W-h/g)	Requirement kW
				Applied Ozone Dose = 20 mg/l					
27	2.5	30	88	17.6	1.8	0.7	189	10.0	1.9
28	4.0	30	85	17.0	2.8	0.7	302	7.5	2.2
				Applied Ozone Dose = 30 mg/l					
27	2.5	20	60	18.0	3.8	1.5	270	6.5	1.7
28	4.0	20	60	18.0	6.0	1.5	432	7.0	3.0
				Applied Ozone Dose = 40 mg/l					
26	1.0	10	60	24.0	4.0	4.0	144	5.5	0.8
27	2.5	20	50	20.0	5.0	2.0	360	7.0	2.5
28	4.0	30	45	18.0	5.2	1.3	562	8.5	4.8

TABLE 21. OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 2.2 TOTAL COLIFORM/100 ML WITH FILTERED SECONDARY EFFLUENT EMPLOYING OXYGEN CARRIER GAS (Required Absorbed Ozone = 35 mg/l)

Figure number	Q_{liq} liquid flow (l/s)	Y_1 ozone concentration (mg/l)	% T.E. transfer efficiency (percent)	A absorbed ozone (mg/l)	Q_{gas} gas flow (l/s)	G/L gas to liquid ratio	Ozone output (g/h)	Power (W-h/g)	Requirement kW
			Applied ozone dose = 50 mg/l						
26	1.0	30	65	33	1.7	1.7	180	10.0	1.8
27	2.5	60	70	35	2.1	0.8	450	13.0	5.9
28	4.0	70	65	33	2.9	0.7	721	14.0	10.1
			Applied ozone dose = 60 mg/l						
26	1.0	30	60	36	1.7	1.7	180	10.0	1.8
27	2.5	50	58	35	3.0	1.2	540	11.5	6.2
			Applied ozone dose = 70 mg/l						
26	1.0	24	50	35	2.9	2.9	252	6.5	1.6
27	2.5	50	50	35	3.5	1.4	630	11.0	6.9

SECTION 6

DISCUSSION

During the water quality evaluation phase of the project, ozone disinfection experiments were initially conducted with nitrified, filtered nitrified, secondary and filtered secondary effluents. The filtered and unfiltered nitrified effluent data from this water quality evaluation phase were combined to be indicative of filtered nitrified water quality because of the consistently low suspended solids levels. The filtered and unfiltered secondary effluent data were also combined to be indicative of filtered secondary effluent. Throughout the remainder of the project both effluents were filtered prior to ozonation experiments to maintain consistency of water quality and reduce variability in suspended solids values. Therefore, all the experimental data developed throughout the duration of the project were characterized as filtered nitrified or filtered secondary effluents. These two effluents were found to be significantly different with respect to COD, NH_3-N and initial total coliform counts.

Over the wide range of operating conditions, conducted during the entire project period, good correlation was observed between total coliform reduction and absorbed ozone, and between total coliform reduction and effluent total residual oxidants, irrespective of carrier gas (air or oxygen). Disinfection performance in terms of absorbed ozone or residual oxidants was independent of the type of carrier gas. The log total coliform reduction was found to be a function of the ozone utilized, with the more ozone transferred into the effluents the better the bactericidal effect and the higher the residual oxidants up to the point where high level disinfection was achieved. Plotting the log total coliform reduction (Log No/N) as a function of the log absorbed ozone concentration allowed consideration of both the initial total coliform value as well as the desired or observed disinfection level for either effluent.

Different relationships were developed for each effluent due to the difference in the amount of absorbed ozone required to achieve a given coliform level with the two water quality types. The total residual oxidants concentrations required to achieve 70 and 2.2 total coliform counts per 100 ml for each effluent type did not appear to be significantly different. Approximately 7 to 8 mg/l total residual oxidants was required in both effluents to

achieve less than 2.2 total coliforms per 100 ml. With the better water quality (nitrified), the residual oxidants concentration increased at a much faster rate as the absorbed ozone concentration increased. Larger absorbed ozone concentrations were required to satisfy the higher ozone demand of the poorer water quality (secondary) and provide the residual oxidants concentration required for disinfection.

From the disinfection results presented, it is apparent that the required absorbed ozone concentration to achieve a specific coliform objective, such as high level disinfection, will vary from plant to plant depending on the nature and type of wastewater to be disinfected. The disinfection efficiency is a function of the amount of ozone transferred into the effluent and the amount of total residual oxidants. Since the absorbed ozone required to achieve a specified disinfection level in a particular effluent is dependent on water quality, the required ozone dose should be determined experimentally prior to design of ozone disinfection systems. Effluent pretreatment, such as filtration prior to disinfection, may be advantageous by reducing the ozone demand of the effluent and insuring a consistent water quality.

The factors affecting ozone disinfection performance (i.e., water quality, ozone transfer efficiency and absorbed ozone) are key factors in evaluating the feasibility and economics of designing ozone systems for effluent disinfection. Variables such as retention time or contact time appear less important and can be overemphasized, however, transfer efficiencies increased with increased retention time. Requirements for obtaining the desired disinfection performance efficiently should be established for each specific application.

Since water quality influences both the ozone dose requirements and the transfer efficiency, the gas-liquid contacting system capabilities must be defined. The ozone contacting system cannot be optimized independently of the ozone generating equipment, because transfer efficiency in the contactors and power requirements for ozone generation are both related to ozone concentration in the carrier gas and the carrier gas flow rate.

Ozone generating equipment is typically compared on the basis of "rated capacity" such as ozone output, ozone concentration and production efficiency at a maximum ozone production rate. This information provides a comparison at one operating point only. However, during actual operation the ozone output (concentration and gas flow rate) may vary over several operating conditions. Therefore, an evaluation of ozone production efficiencies over the expected operating conditions should be considered for proper equipment selection.

The generator mapping procedure previously described provides a means to determine the economical generator operating range for ozone production. The ozone contacting system capabilities must also be defined for optimization of the total system (generation and contacting). The optimum obtainable ozone transfer efficiency compatible with economic ozone production required to achieve the disinfection objectives can then be determined. This interrelationship between ozone generation and ozone contacting must be understood by the design engineer for efficient and economical design of ozone systems.

The impacts of carrier gas ozone concentration, carrier gas flow rate, gas to liquid ratio, and applied ozone dose on contactor ozone transfer efficiency employing a given water quality were defined. The impacts of different water qualities on contactor ozone transfer efficiency were also established. At the same absorbed ozone requirements of 15 to 20 mg/l in the filtered secondary and filtered nitrified effluents, applied ozone doses of 20 and 30 mg/l, respectively, were required during operation with air carrier gas. The lower applied dose for the secondary effluent was due to the higher transfer efficiency. At this absorbed ozone concentration of 15 to 20 mg/l, disinfection levels of 2.2 total coliforms/100 ml were achieved in the nitrified effluent, while the disinfection level attained with secondary effluent was 70 total coliforms/100 ml.

The ozone system was capable of achieving a disinfection level of 2.2 total coliforms/100 ml with nitrified effluent over the diurnal flow ranges investigated, but it was not capable of achieving this level of disinfection with secondary effluent during operation with air carrier gas. The high absorbed ozone requirements for this level of disinfection with secondary effluent necessitated higher ozone concentrations that were achieved only by converting the system to oxygen carrier gas for ozone generation. The higher ozone concentrations and lower gas to liquid ratios achievable with oxygen feed gas provided higher transfer efficiencies at the higher applied dose requirements.

Under identical operating conditions of applied ozone dose, carrier gas ozone concentration, gas to liquid ratio and wastewater flow rate, the percent ozone transferred into the effluent was found to be independent of the type of carrier gas (air or oxygen) employed. At the high absorbed ozone requirements to achieve high level disinfection, operation with oxygen carrier gas offered two distinct advantages. Power requirements for ozone production (generator only) from oxygen were significantly less than the production requirements from air. Ozone contactor transfer efficiencies were higher during oxygen operation due to the higher ozone concentrations and lower gas to liquid ratios available to achieve the same applied dose requirements.

The differences in generator power requirements for air versus oxygen generation of ozone with the ozonation system at Marlborough, Massachusetts are summarized in Tables 22, 23 and 24 for achieving the desired disinfection objectives. Tables 22 and 23 present the operating conditions required to achieve 70 and less than 2.2 total coliforms per 100 ml with filtered nitrified effluent, respectively. Table 24 presents the operating conditions required to achieve 70 total coliforms per 100 ml with filtered secondary effluent. The ozonation system was not capable of effectively achieving less than 2.2 total coliforms per 100 ml in secondary effluents during operation with air carrier gas.

Power requirements for oxygen production as a function of air preparation would have to be considered to evaluate the actual total difference in power requirements for air versus oxygen operation. The total system power requirements for carrier gas preparation, ozone production, ozone contacting and ozone destruction could then be evaluated for comparison of air versus oxygen operation.

The capability of ozone to reliably disinfect filtered nitrified and filtered secondary effluents to stringent standards of 2.2 and 70 total coliforms respectively was demonstrated. To be considered a reliable system, the ozonation operation must also possess reliable process control parameters, process instrumentation, and equipment.

The good correlations between absorbed ozone concentration and total residual oxidants concentration compared to total coliform reduction indicate their usefulness and applicability as process control parameters. The Dasibi ozone gas monitor and the Delta Scientific residual ozone monitor provided reliable, instrumentation capabilities. Proper calibration and maintenance were required on both units to provide proper performance. The Delta Scientific residual ozone readings correlated well with the total residual oxidant levels (determined amperometrically) and were generally 60 percent of those levels.

The major pieces of equipment to be evaluated for reliability include; air preparation equipment, ozone generator and ozone contactors. The pilot system silica gel driers were somewhat atypical in that the economics of full scale systems would dictate air chillers followed by smaller silical gel driers. Performance of such drying systems can be monitored and controlled by dried gas dew point measurement. The air drying equipment required for full scale systems is typical of accepted industrial applications and should be considered reliable although not specifically demonstrated during this study.

The generating equipment provided a consistent ozone output. Variations were small and easily identified by monitoring ozone output at known operating conditions. Maintenance requirements to

TABLE 22. COMPARISON OF OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT FOR AIR VERSUS OXYGEN CARRIER GAS (Required Absorbed Ozone = 8-10 mg/l)

Q_{liq} liquid flow (l/s)	Absorbed Ozone (mg/l)		Ozone output (g/h)		Power requirements			
					W-h/g		kW	
	Air	Oxygen	Air	Oxygen	Air	Oxygen	Air	Oxygen
	Applied Ozone Dose = 20 mg/l							
1.0	9.6	-	72	-	13	-	0.9	-
2.5	9.6	11.0	180	180	14	5.5	2.5	1.0
4.0	9.6	8.4	288	288	16	5.5	4.6	1.6
	Applied Ozone Dose = 30 mg/l							
1.0	10.2	-	108	-	13	-	1.4	-
2.5	10.2	10.2	270	270	15	5.5	4.1	1.5
4.0	10.2	10.2	432	432	17	6.0	7.3	2.6

TABLE 23. COMPARISON OF OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 2.2 TOTAL COLIFORMS/100 ML WITH FILTERED NITRIFIED EFFLUENT FOR AIR VERSUS OXYGEN CARRIER GAS (Required Absorbed Ozone = 15-20 mg/l)

Q_{liq} liquid flow (l/s)	Absorbed Ozone (mg/l)		Ozone output (g/h)		Power requirements			
					W-h/g		kW	
	Air	Oxygen	Air	Oxygen	Air	Oxygen	Air	Oxygen
			Applied Ozone Dose = 30 mg/l					
1.0	20.4	-	108	-	14	-	1.5	-
2.5	16.5	15.0	270	270	19	7.5	5.1	2.2
4.0	15.0	15.0	432	432	25	8.5	10.8	3.7
			Applied Ozone Dose = 40 mg/l					
1.0	21.6	-	144	-	16	-	2.3	-
2.5	16.8	16.0	359	360	20	7.5	7.2	2.7
4.0	-	16.0	-	576	-	7.5	-	4.3

TABLE 24. COMPARISON OF OZONE GENERATING-CONTACTING CAPABILITIES FOR ACHIEVING 70 TOTAL COLIFORMS/100 ML WITH FILTERED SECONDARY EFFLUENT FOR AIR VERSUS OXYGEN CARRIER GAS (Required Absorbed Ozone = 15-20 mg/l)

Q_{liq} liquid flow (m^3/hr)	Absorbed Ozone (mg/l)		Ozone output (g/h)		Power requirements			
					W-h/g		kW	
	Air	Oxygen	Air	Oxygen	Air	Oxygen	Air	Oxygen
			Applied Ozone Dose = 20 mg/l					
1.0	15.6	-	72	-	-	-	-	-
2.5	16.0	17.6	180	189	17	10.0	3.1	1.9
4.0	16.0	17.0	286	302	19	7.5	5.4	2.2
			Applied Ozone Dose = 30 mg/l					
1.0	18.0	-	108	-	14	-	1.5	-
2.5	18.0	18.0	270	270	17	6.5	4.6	1.7
4.0	18.0	18.0	431	432	19	7.0	8.2	3.0
			Applied Ozone Dose = 40 mg/l					
1.0	18.4	24.0	144	144	14	5.5	2.0	0.8
2.5	18.4	20.0	360	360	16	7.0	5.8	2.5
4.0	-	18.0	-	562	-	8.5	-	4.8

replace ozone generating tubes were quickly and easily completed. The equipment reliability of the ozone contacting equipment was maintained with simple maintenance, typical of motors and rotating equipment.

The results and operating experience obtained during this study indicate the effluent ozonation disinfection system to be reliable. The ozone disinfection performance, process control parameters, instrumentation, and major process equipment all exhibited reliable performance.

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